NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 855

RELATION BETWEEN SPARK-IGNITION ENGINE KNOCK, DETONATION WAVES, AND AUTOIGNITION AS SHOWN BY HIGH-SPEED PHOTOGRAPHY

By CEARCY D. MILLER

1946

AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s² or 32.1740 ft/sec²

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m⁻⁴-s² at 15° C and 760 mm; or 0.002378 lb-ft⁻⁴ sec²

Specific weight of "standard" air, 1.2255 kg/m³ or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

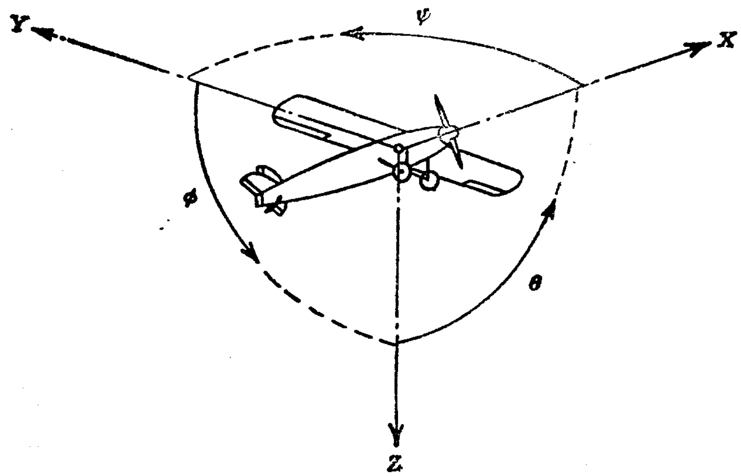
ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	φ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter
p Geometric pitch
p/D Pitch ratio
V' Inflow velocity
V_s Slipstream velocity
T Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$
P Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{P n^2}}$
η Efficiency
n Revolutions per second, rps
Φ Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph
1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft

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By Cearcy D. Miller

SUMMARY

A critical review of literature bearing on the autoignition and detonation-wave theories of spark-ignition engine knock and on the nature of gas vibrations associated with combustion and knock results in the conclusion that neither the autoignition theory nor the detonation-wave theory is an adequate explanation of spark-ignition engine knock. A knock theory is proposed, combining the autoignition and detonation-wave theories, which introduces the idea that the detonation wave develops in autoignited or after-burning gases and ascribes comparatively low-pitched heavy knocks to autoignition but high-pitched pinging knocks to detonation waves with the possibility of combinations of the two types of knock.

Analysis of five shots of knocking combustion, taken with the NACA high-speed motion-picture camera at the rate of 40,000 photographs per second reveals propagation speeds ranging from 3250 to more than 5500 feet per second. The range of propagation speeds from 3250 to more than 5500 feet per second is held to be consistent with the proposed combined theory but not with either the simple autoignition theory or the simple detonation-wave theory.

INTRODUCTION

Knock is one of the most serious limitations on the performance of the current reciprocating aircraft engine. Even in cases where it is not the primary limitation on performance, knock imposes the most severe requirements upon the aircraft-engine fuel and limits the quantity of fuel available for use in high-performance aircraft engines. Knock has been plaguing the designers and users of spark-ignition engines in general at least since 1880 at which time Clerk suppressed extremely violent knock by use of water (reference 1). Knock has been the subject of intensive research by groups in various countries for about 25 years.

The past researches on knock have uncovered an immense amount of information, not only concerning the basic nature of knock but also concerning the question of what to do about it. The information available on the basic nature of knock has led most writers, at least in the United States, to accept the autoignition theory in preference to all others. (Though many writers refer to knock as "detonation," they do not mean to imply that they believe knock is caused by a detonation wave.) Only a few dissenters (references 2 to 9) have questioned the adequacy of the autoignition theory. The available information on what should be done about knock is outside the scope of this paper and is so well known as to need no review here. The available information is undoubtedly accurate as far as it goes and is so extensive that many practical workers with engines and fuels even discount the need for definite knowledge as to what knock is.

Probably the most important reason for an exact determination of knock is associated with the fact that little is definitely known even about the harmfulness of knock. As will be shown in this paper, there are probably more than one and perhaps even more than two phenomena that are regarded as knock when they occur in the combustion chamber. In view of the possibility that these phenomena may not all be harmful, it seems urgently desirable to learn which are harmful and how to distinguish between one of the phenomena and another. As was pointed out by Boerlage in 1936 (reference 6), the noise of knock cannot be regarded too seriously until the harm done has been demonstrated to be proportional to the noise. In order to distinguish between the forms of knock and to know which are harmful and which not, the logical first step appears to be that of learning what the phenomena are and under what conditions the various phenomena occur.

Other reasons for seeking the true explanation of knock are the possible saving of much labor involved in developing and testing ideas based on a possibly false conception of the nature of knock, the acquisition of additional fundamental knowledge concerning chemical laws that might prove useful in other fields, and the possibility, however remote, that some new and simpler solution to the knock problem might be suggested.

Next to autoignition, the detonation-wave theory probably is generally regarded as the most plausible of the many theories that have been advanced to explain knock. Though the author and coworkers questioned the adequacy of the autoignition theory in references 7 to 9, no support for the detonation-wave theory is offered in those papers. Later developments have led the author to believe, however, that a detonation wave, or some phenomenon very much like a detonation wave, actually is involved in the type of knock most frequently encountered in the modern aircraft engine. Autoignition also appears to be often involved in knock. This paper presents a combined autoignition and detonation-wave theory based on a study of NACA high-speed photographs and of the available literature concerning knock, which was developed at the NACA Cleveland laboratory during 1944.

The autoignition and detonation-wave theories of knock are actually in agreement in many respects. According to either theory, knock occurs only after the flame has traveled from the spark plug through most of the fuel-air mixture at a speed ranging from below 50 feet per second to several hundred feet per second, depending on engine speed, fuel-air ratio, and a number of other variables. This speed of 50 to several hundred feet per second is a low speed with regard to the tendency to produce shock; it is the normal rate of burning in nonknocking operation. Again according to either theory, the shock known as knock is produced by the sudden inflammation of the end gas, the gas that has not yet been ignited at the time knock occurs by the normal travel of the flame from the spark plug.

If the end gas is considered as being divided into a very large number of extremely small cells or increments, it is clear that no great shock will result from the burning of the individual increments at widely different times, however fast the burning of each increment may be, and it is also clear that shock will not result from the simultaneous burning of all the increments unless each increment goes through the burning process within an extremely small time interval. Shock will result, according to either theory, only if each increment burns within a very small time interval and all increments burn at the same time within a very small limit. If these two conditions are satisfied, then the end gas does not have time to expand during the burning of the increments and a high pressure is produced in the end gas relative to the gas in the other parts of the chamber. The subsequent expansion of the end gas sets up a violent vibration or system of standing waves throughout the entire contents of the combustion chamber. Such a system of standing waves was shown to be the cause of audible knock, at least under certain conditions, by the research reported by investigators at M.I.T. and at General Motors between 1934 and 1939 (references 10 to 12). Slow-motion pictures of these vibrations taken at 40,000 photographs, or frames, per second were presented in 1940 (reference 13).

The only point of difference between the autoignition and detonation theories is in the means of synchronizing the ignition of the end-gas increments, that is, the mechanism that causes all end-gas increments to burn at the same time within a small enough limit to cause shock.

The argument presenting the synchronizing mechanism of the autoignition theory is as follows: Each end-gas increment will burn explosively when it attains some certain combination of temperature and density (or the equivalent of some particular temperature-density history, as suggested in reference 14). All end-gas increments are adiabatically compressed at the same time and at the same rate by the expansion of the burning gas behind the flame front. All increments of end gas should therefore reach the critical combination of temperature and density at which they will explode at the same time.

In an analysis of the synchronizing mechanism of the autoignition theory, the compression of the end gas by the burning gases should be considered to be accomplished by an infinite series of sound waves. A given condition of temperature and density should therefore be expected to travel through the end gas from the burning zone at the speed of sound. The combination of temperature and density in any end-gas increment may be expressed as some function F, so defined that each end-gas increment will explode when $F=F_{cr}\pm\delta$, the term δ representing an element of uncertainty due to random variation in the behavior of the end-gas increments or to random inhomogeneities. The value of F in each end-gas increment will increase by an amount equal to 2δ in some time interval τ. Now, if τ is not greater than the order of the time interval τ' required for a sound wave to pass through the unignited end gas, then it should be expected that autoignition would take place as an explosive reaction traveling through the unignited end gas at least at the speed of sound. It would not take place as a simultaneous reaction throughout the end gas because the end-gas increments nearer to the normal burning zone would reach the condition $F=F_{cr}\pm\delta$ progressively earlier than the end-gas increments farther from the normal burning zone. The explosive reaction would constitute some kind of explosive wave, if not an actual detonation wave. This wave might travel too slowly to produce shock and to be regarded as a true detonation wave. Obviously, however, the less shock the wave produced, the less the knocking sound heard outside the engine.

If τ is assumed to be much greater than the order of τ', then autoignition should be expected to develop homogeneously throughout the end zone because only an insignificant fraction of the end-gas increments near the normal burning zone would reach the condition $F=F_{cr}\pm\delta$ earlier than the end-gas increments far from the normal burning zone; in general the increments far from the normal burning zone would reach the condition $F=F_{cr}\pm\delta$ during the same period of time as the increments near the normal burning zone. The pressure built up by the combustion of the end gas, however, is relieved also by an infinite series of sound waves. Consequently, if τ is many times greater than the order of the time interval τ'' required for a sound wave to pass through the autoigniting end gas, the pressure in the end gas would be relieved many times during the process of autoignition and shock would not occur.

The magnitude of the time interval τ apparently must lie within a range somewhat greater than τ' but not many times greater than τ'' if knock is to be caused by a homogeneous autoignition of the end gas. Above this range of values for τ no shock can occur; below this range of values the autoignition must occur as something similar to a detonation wave and becoming more and more like a detonation wave as the knock intensity increases. (Knocks of different intensity can occur with the same end-zone volume according to unpublished NACA photographic records.) The time interval τ'' is a variable for different stages of the homogeneous autoignition process and reaches a value much less than τ' during the later stages of the process. The range of values of τ greater than τ' but not many times greater than τ'' must therefore be quite narrow.

Autoignition, either as a detonation wave or as a homogeneous reaction with τ slightly greater than τ', seems a very plausible synchronizing mechanism. Before it is accepted conclusively, however, the available evidence should be carefully studied as to whether it actually is an adequate synchronizing mechanism. The evidence should also be investigated as to whether autoignition of the individual gas increments proceeds to completion within a short enough time interval to produce shock. A considerable amount of evidence exists against autoignition as the sole cause of the standing waves of knock on both counts, as will be discussed in the later parts of this paper.

The synchronizing mechanism postulated by the detonation-wave theory is an intense compressive shock wave that travels through the end gas at supersonic velocity. Each gas increment is ignited probably by the combination of the sudden intense compression occurring in the shock front, the action of chain carriers in the shock front, and the radiation of heat from the shock front. The entire combustion, or some definite stage of the combustion, of each gas increment is presumed to occur in the shock front and to release a large amount of energy immediately behind the shock front. The energy released by the gas increments immediately behind the shock front maintains the high pressure required to propagate the shock front through the charge. Such a phenomenon, being an intense shock wave, would obviously set up vibration of the gases throughout the combustion chamber.

The photographs of knocking combustion taken at the NACA laboratories at the rate of 40,000 frames per second have been difficult to interpret because of the focal-plane-shutter effect of the camera (reference 15). An examination of figure 5 of reference 16 shows the possible development of a detonation wave as modified by the focal-plane-shutter action. In order to aid interpretation of this qualitative consideration, a quantitative formula for determining propagation rates from the high-speed photographs was developed, the focal-plane-shutter effect being taken into account. The quantitative formula could be applied to only a small percentage of the photographic shots because of the absence of necessary reference points in most cases. In five cases, however, where the formula could be applied it has given knock propagation speeds as great as or greater than the speed of sound in the burned gases. The development of the formula and its application to the five cases, all taken from previous NACA reports, are presented in the second part of DISCUSSION AND ANALYSIS.

The conclusion that knock, in at least five cases, involves a disturbance traveling at the speed of sound or faster led to a reexamination of the literature for evidence for and against both autoignition and detonation as the cause of knock. This examination of previous literature, including the previous NACA reports, led to the conclusion that both autoignition and detonation waves are involved in knock. The mechanism responsible for the initiation of the detonation wave has not been included within the scope of the paper. The literature review is presented in the first part of DISCUSSION AND ANALYSIS. References are made, in general, only to such literature as has a direct bearing on the arguments presented; no attempt has been made to include a complete bibliography covering the subject of knock. An attempt was made, in the conduct of the review, to examine all photographic evidence available. The references included in this paper, together with their own references and bibliographies, should form a fairly complete bibliography with the exception of possible work done during war years, which is not yet available.

DEFINITIONS OF TERMS

Throughout the present paper the following terms are used with the meanings indicated:

knock—Any type of reaction occurring within the combustion-chamber contents and producing objectionable noise outside the engine but not including the phenomenon of early combustion caused by too-early spark timing or by early ignition from a hot spot.

explosive knock reaction—A specific reaction observed in NACA photographs of knocking combustion, taken at 40,000 frames per second, usually appearing instantaneous when the photographs are projected at the normal rate of 16 frames per second and coinciding chronologically with the onset of gas vibrations as seen in the photographs. (This reaction, being regarded as one form of knock, will sometimes be referred to simply as "knock" when the context makes the meaning clear.)

flame front—The continuously changing surface that separates uninflamed parts of the cylinder charge from the burning parts of the charge that have been ignited by the advance of the flame from the spark plug.

autoignition—Spontaneous burning in any part of the cylinder charge not caused by a spark, by contact with a flame front, or by contact with a hot spot, and including not only the initiation of burning but the entire process of burning resulting from the spontaneous ignition.

shock wave—An intense compressive wave, traveling through gas at supersonic velocity, the front of such wave constituting an abrupt increase or practical discontinuity in temperature, density, and velocity of the gas.

detonation wave—A type of wave often observed in long tubes consisting of a shock wave traveling through a gas or a gas mixture and causing a reaction of the gas in the shock front, such reaction releasing energy immediately behind the shock front, the energy so released serving to maintain the pressure needed behind the shock front to propagate the wave.

DISCUSSION AND ANALYSIS

ARGUMENT FOR COMBINED AUTOIGNITION AND DETONATION-WAVE THEORY OF KNOCK BASED ON PUBLISHED WORK OF VARIOUS INVESTIGATORS

The autoignition theory.—The autoignition theory of knock was suggested by Ricardo in 1919 (reference 17). Two years later Woodbury, Lewis, and Canby of the du Pont laboratories (reference 18) presented streak photographs of combustion in a bomb, taken by the method of Mallard and Le Chatelier (reference 19), and drew conclusions favoring the autoignition theory. These du Pont investigators seem to have regarded the detonation-wave theory as the one having had general credence up to that time. From an analysis of their streak photographs and from consideration of various facts reported by previous investigators they concluded that "the possibility of detonation under such conditions [conditions existing in the engine cylinder] appears exceedingly remote." After mentioning that detonation is set up in a closed cylinder of small dimensions only with great difficulty they further stated: "On the other hand, autoignition of the high-density gases ahead of the flame front occurs over a wide range of fuel mixtures and conditions [in their tests] and gives a sudden development of pressure similar, in our opinion, to that characteristic of a knocking explosion. It is possible that this autoignition may set up detonation [a detonation wave] in some cases, thereby acting as an intermediate stage in knocking. Our experiments have not been carried to a definite conclusion, and present data do not warrant presentation of autoignition as a positive explanation for knocking. It is our feeling, however, that information at hand favors more strongly the theory of autoignition of the high-density gases ahead of the flame front than that of detonation [the detonation wave]."

In 1936 Withrow and Rassweiler (reference 20) presented some excellent photographs of knocking combustion that showed the development of autoignition in the end gas. These photographs, taken at the rate of 2250 frames per second, greatly increased the already existing confidence in the autoignition theory. They were taken at too low a rate to show a detonation wave, however, even though such a wave might actually have occurred after the autoignition that was photographed.

The autoignition theory, with the additional assumption of preflame chain reactions, has the advantage of explaining and correlating many of the known facts concerning knock. During the period 1939 to 1945, however, urgent need for a modification of the simple autoignition theory of knock has been shown by photographs of knocking combustion taken at the rate of 40,000 frames per second with the NACA high-speed motion-picture camera. The first of these photographs, presented in 1940 and 1941 (references 13 and 16), showed a reaction completed in 50 microseconds or less. The authors believed that this reaction was the true knock reaction because they could see in the projected motion pictures that this reaction occurred at the same time as the beginning of the violent vibration of the gases, which by then had come to be regarded as an indication of knock. Later NACA tests (reference 8) showed that this extremely quick reaction did occur simultaneously with the beginning of the vibrations. Serruys had previously concluded that knock generally occupies a time interval less than 100 microseconds in reference 21 and, on a basis more in harmony with the standing-wave concept of knock, in reference 22. Considerations presented in the present paper have caused the author to abandon the exclusiveness of the concept "true knock reaction." The reaction will hereinafter be referred to as the "explosive knock reaction."

The need for a modification of the autoignition theory of knock lies in the fact that the evidence available in the literature indicates autoignition requires for its completion a time interval of an entirely higher order than the 50 microseconds involved in the explosive knock reaction, even under conditions of severity approaching those of the modern aircraft engine. The previously mentioned photographs of reference 20 clearly show brightly luminous autoignition occupying a time interval of the order of 1000 microseconds. High-speed photographs presented in reference 9 have shown autoignition flames slowly propagating themselves from point to point throughout the end gas before the explosive knock reaction occurs; and another high-speed photograph in reference 16 has shown autoignition developing slowly and simultaneously in all parts of the end gas before the occurrence of the explosive knock reaction. The autoignitions shown in the photographs of references 9 and 16, preceding the explosive knock reaction, occupied time intervals ranging from 500 to 1250 microseconds. Streak photographs were published as early as 1911 by Dixon and coworkers (references 23 and 24) showing slow autoignition in glass tubes resulting from quick compression. This autoignition progressed at a rate comparable with the rates of the autoignitions shown in references 9, 16, and 20.

The evidence showing that autoignition occupies a time interval of a higher order than 50 microseconds is not the only reason for believing simple autoignition to be an inadequate explanation of knock. Many investigations have shown that autoignition can occur without causing marked gas vibrations, which are probably the best-known characteristics of knock in the present-day spark-ignition engine. These gas vibrations, if they occur, are visible in streak photographs taken by the method of Mallard and Le Chatelier (reference 19) as a series of bright bands extending across the photograph in a direction perpendicular to the direction of film movement. The gas vibrations also cause oscillations in pressure-time records.

Some excellent streak photographs presented by Withrow and Boyd (reference 25) are examples of nonvibratory autoignition in the engine cylinder. These General Motors investigators stated that both the pressure-time records and the flame traces show that the autoignition required 2° to 5° of crankshaft rotation (400 to 1000 microsec) for its completion. Figures 11 to 16 of reference 25 clearly show the flame front traversing the greater part of the chamber at the normal rate and show the end gas then being consumed at a much higher rate. All of these figures except figure 14, however, reveal not the slightest indication of gas vibrations. It is difficult to conclude from the printed picture of figure 14 whether there is any evidence of vibrations. Moreover, the pressure-time records of figures 11 to 16 show no evidence of gas vibrations. Though audible gas vibrations probably did not occur in the tests of reference 25, some kind of disturbing noise surely must have occurred, as is discussed in this paper in the section entitled "Detonation-wave and autoignition theories combined."

The authors of reference 25 did not comment on the absence of gas vibrations. Up to about the time of the writing of that paper (1931), gas vibrations did not seem to have been regarded as a usual feature of knock. The only recognized criterion of knock as seen in pressure-time records appears to have been simply a sharp increase in the rate of pressure rise. In 1932 Rassweiler and Withrow presented in reference 26 streak photographs clearly showing the gas vibrations; and in 1934 they showed that the vibrations as seen in the photographs coincided, cycle by cycle, with fluctuations shown on the pressure-time records (reference 11).

Woodbury, Lewis, and Canby in 1921 did not regard the gas vibrations as being associated with knock, for in the previously quoted passage from reference 18 they concluded on the basis of their own experiments that autoignition of the high-density gases ahead of the flame front gives a sudden development of pressure similar, in their opinion, to that characteristic of a knocking explosion. The pressure-time traces presented in reference 18 for the cases of autoignition referred to showed, in general, no gas vibrations but only a sharp increase in rate of pressure rise near the end of combustion. Almost without exception the streak photographs also showed no trace of gas vibrations; the exception was with ether-air mixtures. With initial temperature of 150° C and initial pressure of 65 pounds per square inch neither the flame trace nor the pressure-time trace for an ether-air mixture showed any sign of gas vibrations, whereas with the same initial temperature and with an initial pressure of 75 pounds per square inch both the flame trace and the pressure-time trace showed the gas vibrations with agreement in frequency. The change that occurred in the phenomena studied in a bomb by these investigators, when passing from 65 pounds per square inch to 75 pounds per square inch with ether-air mixture at 150° C, appears to correspond to the change in the recognized criterion of spark-ignition engine knock that developed in the early 1930's.

No particular note appears to have been made in the literature of the change in the recognized criterion of knock that developed in the early 1930's. Sufficient data do not appear to be available at this time to explain the change or to indicate whether it was a real change caused by altered engine design and altered fuels or an apparent change developing with the securing of more extensive data.

In 1939 (reference 27) Boyd compared a streak photograph of autoignition without gas vibrations (fig. 10 of reference 27, same as fig. 16 of reference 25) and a streak photograph of autoignition with gas vibrations (fig. 12 of reference 27, same as fig. 10 of reference 26). He very reasonably regarded the case of figure 12 as involving a much more violent knock than the case of figure 10. Examination of figures 10 and 12 of reference 27, however, discloses that the end zone was of nearly the same size in the two cases at the time the autoignition, or knock, occurred. The comparison therefore indicates that the violence of knock or at least the violence of the gas vibrations is not dependent on the size of the autoigniting end zone. Moreover, NACA high-speed photographs have shown plainly visible gas vibrations in cases where the end zone, if any existed at the time of start of the gas vibrations, was too small even to be seen in the photographs (references 7 and 8).

Other streak photographs showing autoignition without trace of gas vibrations may be found in references 28 to 30. The most striking examples of this phenomenon, however, are to be found in the work of Duchêne (reference 31). In this work many streak photographs are presented of combustion, with spark ignition, in a bomb equipped with a piston providing compression by a blow from a heavy pendulum. Many of these flame traces show a sudden darkening extending entirely across the trace, which Duchêne considered as indicative of a detonation wave. Only three of the records, however, 21, 35, and 36, show any trace of gas vibrations. In most cases the darkening is quite diffuse instead of practically instantaneous, as it should be if caused by a detonation wave. The records all distinctly show slow autoignition preceding the sudden darkening. The fraction of the total charge involved in the nonvibratory autoignition in the different records covers the entire range from near zero to practically the entire charge. Gas vibrations should not, of course, be expected from simultaneous autoignition of the entire charge at constant volume. Records 23, 28, 29, and 31 of reference 31, however, clearly show autoignition of about half the contents of the chamber without any trace of vibrations.

The inadequacy of simple autoignition as an explanation of the phenomenon of knock has been clearly recognized by some investigators. In 1928 Maxwell and Wheeler (reference 2) reported frequently observing autoignition flame, with 50–50 mixtures of pentane and benzene in a bomb, starting from the far end of the cylinder and progressing back to meet the spark flame. They reported that explosions in which this phenomenon occurred were no louder than usual and that the pressure records showed no unusual features. They concluded, in consequence, that such an ignition of unburnt residual mixture is not likely to be the cause of a "pinking" explosion in an engine cylinder. The same investigators stated in reference 3: "Our objection to the 'autoignition' theory is that, when such ignitions occur during an explosion in a closed cylinder (e. g., Figs. 2 and 5), the explosion is no more violent than in their absence. Moreover, what we have termed a 'pink' in our cylinder, because it so closely resembles the pink in an engine cylinder, is obtained most commonly without the occurrence of 'autoignition'."

In 1935 Egerton, Smith, and Ubbelohde (reference 4), in discussing the work of other investigators, stated: "'Autoignition,' i. e. ignition in a region of the gas prior to the arrival of the flame front, was observed both in the knocking zone and elsewhere, but does not necessarily give rise to the knocking type of combustion, though it was supposed that the high rate of combustion in the knocking zone was due to autoignition within it."

In 1936 Boerlage (reference 6) in discussing the results of his own streak photographs stated: "What surprised us, however, in the results obtained with the test engine, was the relatively slow character of the combustion due to autoignition. The development of the second center of ignition was at all points similar to the progression of the primary flame due to the spark. The 'simultaneous' combustion of the 'end gas' which we have believed responsible for the knock, thus seems to be reduced to the rather calm development of a secondary center of ignition." He further stated: ". . . the velocity of the secondary flame front is practically equal at each instant to that of the primary flame front. We have never been able to make out any speed equal to the speed of sound, but at most, speeds of 150 meters per second, and these only in the case of excessive detonation [knock]. In the case of slight detonation [knock] the speeds do not attain even half this figure. . . . The pressure diagrams show only moderate pressure rises, and this is still another indirect proof of the fact that the speeds of the flames are relatively low and remain much below the speed of sound. We have not succeeded in demonstrating the existence of extreme local pressures."

The investigations mentioned have shown beyond possible doubt that autoignition can, and in many cases actually does, occur too slowly to cause the gas vibrations characteristic of knock. This fact does not prove that autoignition cannot, under any conditions, occur quickly enough to cause the gas vibrations. It does, however, preclude the possibility of regarding the occurrence or nonoccurrence of autoignition as a criterion for the occurrence or nonoccurrence of the type of knock characterized by gas vibrations. A different criterion must be sought, either the occurrence of autoignition at a rate above some critical value or the occurrence of some other phenomenon.

Indeed the criterion of autoignition at a rate above some critical value seems to be precluded by the NACA photographs of references 9 and 16, for in these cases slow autoignition was seen to occur, followed by the much faster reaction that set up the gas vibrations. In this connection it should be noted that some investigators (references 14 and 32) have regarded the apparent autoignition shown in reference 16 as a preflame reaction. The slow apparent autoignitions shown in reference 9, however, are more difficult to explain as preflame reactions because they propagate themselves from point to point in the same manner and at about the same speed as a normal flame.

The available literature, as reviewed in this section, points to the conclusion that some phenomenon other than simple autoignition must be sought as the cause of the gas vibrations associated with knock in the modern spark-ignition engine.

The detonation-wave theory.—The occurrence of a detonation wave in a bomb or a knocking engine is not supported by any such abundance of direct experimental evidence as the occurrence of autoignition. This fact is, of course, readily explained by the consideration that the detonation wave, being a many times faster phenomenon than autoignition, requires very much more powerful methods for its detection. A very important consideration in favor of the detonation wave as the explanation of gas vibrations is the unquestionable fact that it would cause gas vibrations if it did occur, whereas it has been shown that simple autoignition does not necessarily cause the vibrations when it occurs.

Many writers have long been strongly opposed to the detonation-wave theory of knock, principally because it is very difficult to set up detonation waves in containers as small as an engine cylinder, or indeed in hydrocarbon-air mixtures at all, and because many variables have unlike effects on the tendency of a combustible charge to knock in an engine and to develop a detonation wave in a tube.

In 1936 the Russian investigators Sokolik and Voinov (reference 5) furnished direct experimental evidence of propagated combustion, as contrasted with the concept of simultaneous autoignition, traveling through the end zone in a knocking engine at the correct speed to be regarded as a detonation wave. This evidence is in the form of streak photographs for which a sufficiently high film speed was used to resolve the slope of the luminosity front developed by the detonation wave. It is unfortunate that this work has not, in the past few years, received more careful consideration. The photographs of Sokolik and Voinov were taken through a narrow window extending across the combustion chamber in the direction of the flame travel. The results show the flame traversing the greater part of the chamber at a mean velocity usually less than 20 meters per second, then traversing the remaining part of the chamber at a velocity of the order of 2000 meters per second.

The photographs of Sokolik and Voinov are, of course, open to the criticism that they show the performance of only a narrow zone in the combustion chamber. For this reason, the illusion of a detonation wave traveling at 2000 meters per second could have been caused by a much slower autoignition traveling through the end gas at a considerable angle to the visible zone. Such an illusion should not be expected to be consistent throughout many records. The authors of reference 5, however, do not state how many records they studied.

NACA high-speed motion pictures of knock (references 7 and 8) have suggested that the explosive knock reaction does not necessarily originate in the flame front but that it originates at random anywhere within the normal flame or the autoigniting end gas. For this reason NACA investigators have been slow to accept the results of Sokolik and Voinov as having general validity, suspecting that some difference in test conditions may have caused a type of knocking phenomenon to occur in their work different from any knocking phenomenon that has been found in the NACA investigations.

Intermediate flame velocity.—Intermediate between the slow autoignition found by various investigators and the detonation-wave velocity determined by the authors of reference 5 is the finding by Schnauffer (reference 33) of a speed of 265 to 300 meters per second for the travel of a flame through the end zone in knock. Schnauffer made this determination by means of ionization gaps mounted in different parts of the combustion chamber. The ionization current across the successive gaps was amplified and used to light neon bulbs. The time interval between the lighting of the successive bulbs was measured by the record of the bulbs on a photosensitive drum rotating at high speed.

Flame travel at 265 to 300 meters per second through an end zone 2 to 3 centimeters long would be almost fast enough to satisfy the 50-microsecond limitation imposed by the photographs of reference 16, and such a rate of flame travel might therefore very well be regarded as a satisfactory cause of the explosive knock reaction. Note should be made, however, that the speed of 265 to 300 meters per second has not been verified by other investigators. Schnauffer did not indicate how many ionization gaps were used in the actual knocking zone to determine the velocity of 265 to 300 meters per second. Examination of the pattern of the gap locations as shown in the figures of reference 33 indicates either that the velocity was determined from the time interval between ionization of only two gaps or that the distance over which the velocity was measured was much greater than 2 or 3 centimeters, in which case the 50-microsecond limitation was not satisfied. Measurement of rate of flame travel on the basis of the time interval between ionization of two gaps would not be valid in case of any type of greatly accelerated reaction in the end gas. In such a case the normal flame travel through an indeterminate fraction of the distance between the last two gaps would be erroneously treated as the flame travel across the entire distance; the result would be a meaningless velocity.

In reference 33 Schnauffer showed oscillograph records of the ionization currents produced both by the normal flame and the knock reaction in the end zone. The oscillograph records for the two types of combustion look very much alike. Hastings (reference 34) has shown, with the vibratory type of knock, that the total time interval throughout which ionization currents are measurable in the end gas is only a small fraction of the time interval throughout which the ionization currents are measurable in the earlier-burned parts of the cylinder charge. The similarity in the oscillograph traces of Schnauffer's work therefore indicates that he was dealing with simple autoignition, not vibratory knock.

The nature of gas vibrations.—Many investigators have shown the occurrence of gas vibrations in bombs and in engine cylinders, both by photography and by pressure-time records. When the vibrations were first observed on indicator records, the question was raised whether they were not natural vibrations of the indicator set up by the blow of knock. Undoubtedly in many cases of simple autoignition this explanation was correct. In this connection the observation by Schnauffer in 1931 (reference 35) is of interest. With the ionization-gap method he found apparently simultaneous ignition of end gas amounting to approximately 50 percent of the entire cylinder charge; the indicator record showed no vibrations but only a sharp increase in rate of pressure rise. Schnauffer commented: "Figures 4 and 5 show that with a pressure indicator sufficiently free of inertia it is very well possible to record the knocking blow without the appearance of pressure oscillations. It is thereby demonstrated that the oscillations are not pressure oscillations." When Withrow and Rassweiler in 1934 (reference 11) showed a precise agreement between the oscillations recorded by an indicator and the bright bands on a streak photograph of the combustion, it was no longer possible to doubt the validity of the vibrations recorded by the best indicators.

Examination of the published records of gas vibrations in bombs and in engine cylinders reveals that with comparatively slow-burning mixtures such as are used in the spark-ignition engine these vibrations are generally of two types: with the first type the first cycle of vibration recorded has a larger amplitude than any of the later vibrations and the decay of the vibrations is gradual; with the second type both the build-up and the decay of the vibrations are gradual. A detonation wave, by definition, would cause the first type of vibration but not the second. With autoignition ruled out as a cause of the first type of vibration, the detonation wave is probably the only known physical phenomenon that could cause it. This type of vibration will therefore be referred to hereinafter, for convenience, as the "detonation-wave" type of vibration. Among the many investigations that have shown the detonation-wave type of gas vibration in bombs or engine cylinders, either photographically or by means of pressure indicators, are those of references 5, 7, 8, 11, 16, 18, 22, 26, 27, 30, 36 (fig. 6), 37, and 38.

The type of vibration having a gradual build-up obviously requires a gradual feeding in of energy over a period of many cycles. This gradual feeding in of energy could occur only if the vibrations themselves affected the local rates of combustion, or energy release, in such manner as to speed up the combustion in the high-pressure regions relative to the low-pressure regions. Such an effect would cause any slight accidental vibration to become self-amplifying. The cause of an accidental vibration is not hard to find. Ignition at a point in a vessel will unavoidably send forth a pressure wave which, after reflection from the far wall, will return to the point of ignition and may speed up the combustion upon its arrival. Souders and Brown at the University of Michigan (reference 36) found that a very pronounced occurrence of this type of vibration could be eliminated by shortening their spark commutator contact so as to decrease the intensity of the pressure disturbance at ignition. The type of gas vibration having a gradual build-up will be referred to hereinafter as the "vibratory-combustion" type of vibration.

The possibility, of course, exists that the inertia and damping characteristics of a pressure indicator might cause it to indicate a gradual build-up of vibrations even though the gas vibrations actually were of the detonation-wave type, particularly in cases where the vibration frequency is nearly the same as the natural frequency of the indicator. The failure of such spurious records to occur in practice, however, is indicated by the fact that all the records to be found in the literature fall very distinctly into the detonation-wave or the vibratory-combustion type; there is apparently no middle ground. A middle ground would be expected when the detonation-wave type of vibration is modified by a pressure indicator with only slightly too much inertia to produce a faithful record.

The vibratory-combustion type of vibration, as should be expected, generally occurs in fairly long cylindrical bombs, in which the natural frequency is comparatively low and the total time of flame travel is comparatively long. Under such conditions this type of vibration may occur without any evidence of autoignition, hot-spot ignition, or any other type of combustion except the normal flame from the igniting spark, as in the previously mentioned work at the University of Michigan (reference 36, figs. 5, 7, and 13).

Gas vibrations of the vibratory-combustion type in bombs have also been shown by Hunn and Brown (reference 39), Kirkby and Wheeler (reference 40), Lorentzen (reference 41), Duchêne (reference 31), Wawrziniok (reference 42), and Köchling (reference 43). The photographs of reference 40 show how the vibratory combustion requires a bomb of considerable length. In reference 41 Lorentzen pointed out that the vibrations, which he apparently believed were caused by the same phenomenon as knock in the engine cylinder, could not have been caused by detonation because they set in before the attainment of maximum pressure. The vibrations of reference 31 (records 21, 35, and 36) are of particular interest because they developed long after the charge had been completely inflamed, yet they appear to have been built up gradually. The work of reference 42 showed gradual build-up not only of the vibrations in a bomb but also of the air vibrations outside a knocking engine. It is possible, however, that the forced vibrations of the engine walls built up gradually even with a detonation-wave type of gas vibration in the combustion chamber. The gradual build-up of the air vibrations in this case was very rapid as compared with the build-up of the gas vibrations in the bomb; in fact, this case seems to be the middle ground that is lacking in indicator records exposed directly to gas vibrations within the combustion chamber.

The work of Maxwell and Wheeler (references 2, 3, and 44) seems unique in the fact that they appear to have encountered both vibratory combustion and the detonation-wave type of vibration in the same explosion, the one occurring just before the end of the flame travel and the other just after the flame front reached the far wall of the bomb. There seems to be no reason, however, why the two types of vibration should not occur, one after the other in the same combustion cycle. Moreover, two independent vibrations each of the detonation-wave type can be set up one after the other in the same combustion cycle, as was shown in reference 9.

The very excellent streak photographs by Payman and Titman (reference 45) are probably not pertinent to the present discussion because they involve only much faster-burning mixtures than are ordinarily used in spark-ignition engines. Inasmuch as pressure-time records are not included with the photographs of reference 45, any discussion of the type of vibration set up by the phenomena shown in those pictures would be only speculation.

Detonation-wave and autoignition theories combined.—The foregoing discussion clearly indicates a need for some kind of combination of the detonation-wave and autoignition theories of knock, inasmuch as the occurrence of both autoignition and an apparent detonation wave has been demonstrated in the knocking engine. The combined theory proposed herein requires an affirmative decision on the controversial question as to whether afterburning takes place in a volume of gas for a considerable time after the flame front has passed through that volume of gas, or after the entire volume of gas has become inflamed through autoignition. For the purpose of this discussion "afterburning" will be understood to mean continued oxidation of combustible or any other reaction that causes continued spontaneous expansion of gases or pressure increase at constant volume.

If the concept is accepted of a body of end gas inflamed throughout its entire volume by autoignition, then it would seem reasonable that under severe conditions such an inflamed body of gas might be highly susceptible to the propagation of a detonation wave and that a detonation wave traveling through the inflamed body of gas might be the immediate result of autoignition. Such a high susceptibility to the detonation wave might be caused not only by the high temperature within the inflamed gases but by high concentrations of molecular fragments that might be of importance in the propagation of the detonation wave. If the possibility of a detonation wave traveling through a body of gas previously inflamed by autoignition is accepted, it seems almost necessary also to accept the possibility of such a wave traveling through a body of gas in which afterburning is taking place behind the normal flame front. In this manner a detonation wave could develop without autoignition after the entire contents of the combustion chamber had been ignited by the normal flame front. Larger volumes of inflamed gas at any one instant would be expected, however, with autoignition than without autoignition; therefore, a detonation wave should be expected to develop principally in the autoigniting end gas rather than in afterburning gas behind the flame front.

Concerning the possibility of burning after passage of the flame front through a body of gas, Withrow and Rassweiler (reference 28) concluded that the spectrum of the afterglow emitted by such supposedly afterburning gas is the same as that emitted during the $CO-O_2$ reaction and caused by active CO, O_2, CO_2, or O_3 molecules. They suggested that the $H_2+CO_2 \rightleftarrows CO+H_2O$ reaction is in equilibrium after the flame front has passed and that the afterglow is due to a readjustment of the equilibrium when the pressure and consequently the temperature are increased. They remarked: "The distribution of intensity of the afterglow throughout the combustion chamber accords well with the idea that the emission is by carbon dioxide heated by the increase in pressure brought about by combustion of the rest of the charge."

The suggestion that afterglow is entirely caused by readjustment of equilibrium due to compression does not seem compatible with the results of Stevens' work at the National Bureau of Standards with a soap-bubble bomb, in which no appreciable compression of the earlier-burned gas by the later-burned gas was possible. Stevens' streak photographs in references 46 to 48 show very considerable afterglow. On the other hand, two of his photographs, shown both in reference 49 and reference 50, show only the trace of the luminous flame front without afterglow.

Other sound explanations of the afterglow may exist independent of the concept of afterburning, but the possibility of other explanations only precludes use of the afterglow as support for the afterburning hypothesis; that is, the possibility of such explanations may not be regarded as strong evidence against afterburning.

Lewis and von Elbe (reference 51) have regarded Stevens' results (references 48 and 49) as evidence against the concept of afterburning, stating ". . . thousands of explosions . . . failed to reveal the slightest indication of further expansion of the burned sphere after the flame had traveled across the entire gas mixture." If close measurements are made on figure 2 of reference 46 and figure 2 of reference 48, it seems questionable whether a positive statement can be made that these figures show not even the slightest continued expansion of the luminous zone after the constant-velocity expansion of the spherical shell of flame had come to an end. (The end of the constant-velocity expansion of the flame shell seems to be the only means of determining from the photographs when the flame "had traveled across the entire gas mixture.") In one of the flame traces of figure 4 of reference 50, in which the afterglow is absent, continued expansion is plainly visible after completion of the constant-velocity expansion of the flame shell. The printed reproductions of photographs in reference 47 show the flame-front trace too indistinctly for judgment on continued expansion after completion of the constant-velocity expansion. Figure 2 of reference 46 shows luminosity fading progressively from the outer edge of the luminous sphere toward the center after some slight expansion has possibly taken place; the progressive fading is probably caused by rapid cooling of the outer shell of hot gases after the combustion is nearly complete. Randolph and Silsbee have presented a streak photograph (fig. 4 of reference 52) obtained with the same Bureau of Standards apparatus as used by Stevens, showing continued expansion most distinctly after completion of the constant-velocity expansion. A consideration that must always be given attention in Stevens' photographs, as well as in all photographs taken by flame radiations, is the fact that these photographs may not represent the true flame front because of low luminosity in the early stages of burning and because of the finite exposure time required to make a record on the photosensitive material.

The experimental work reported and the arguments advanced by Lewis and von Elbe in reference 51 were concerned mainly with the question of whether combustion in a constant-volume bomb is complete at the time peak pressure is reached and not with the question of whether peak pressure is reached at the instant the flame front has passed through the last increment of gas. The afterburning required by the proposed combined detonation-wave and autoignition theory would cover a time interval of an entirely lower order than that considered in the question of whether combustion is complete at the instant of maximum pressure. The only consideration offered by the authors of reference 51, other than the photographs of Stevens, that would have a bearing on the question of afterburning on the smaller time scale is the suggestion that with afterburning the sharp breaks obtained with fast-burning mixtures between the rising pressure curve and the cooling curve would not occur. By the same token it might be suggested that the extremely flat pressure maxima of slower-burning mixtures, such as shown in figure 16 of reference 8, would not occur if there were no afterburning.

Probably the strongest experimental evidence against afterburning is the General Motors work presented in references 53 to 56. Tests with a sampling valve (reference 56) showed that free oxygen disappeared from the charge immediately after passage of the flame front, but this evidence is open to the question of whether burning was not completed after the gases were removed from the combustion chamber by the sampling valve. In the work of references 53 to 55, flame-front positions as shown by high-speed motion pictures were checked against pressure rise obtained from indicator records. The results indicated completion of burning at the flame front, with some exceptions in reference 55. This evidence is open to the previously mentioned objection that the photographs may not show the true flame front. The agreement between flame-front positions as shown by the photographs and as calculated from the pressure records on the assumption of complete combustion in the flame front may be a coincidence, or the greater part of the combustion may actually be completed in a very small part of the deep combustion zone.

That the photographs of references 53 to 55 did not actually record the true flame fronts is strongly indicated by the work of reference 8. In this work it was shown that peak pressure was reached, at top center, very nearly at the same time that the schlieren flame pattern completely disappeared from the high-speed motion pictures, or about 10 crank-angle degrees at 500 rpm after the flame front had completely filled the chamber. The finding in reference 8, that peak pressure at constant volume coincides with the final fade-out of the schlieren flame pattern, is supported by the previous demonstration of the same fact in a bomb by Lindner (reference 57).

Other evidence in favor of the concept of afterburning has been furnished by various investigators. The ionization records obtained by Hastings (reference 34) showed ionization persisting over 20° to 30° of crank angle at 2000 rpm with normal combustion. With his records of ionization in the end zone during knock, the persistence had only a fraction of that magnitude. He attributed the difference to the much faster combustion in the end zone during knock. It is of interest, in Hastings' records of ionization with normal combustion, that the ionization did not decrease steadily after passage of the flame front but irregularly with even several sharp increases in ionization after the original passage of the flame front.

Souders and Brown (reference 36) with their streak photographs and simultaneous pressure records of combustion in a constant-volume bomb noted an appreciable increase in pressure after the flame front reached the end of the bomb. Marvin and Best (reference 58), observing flame stroboscopically through small windows mounted in a cylinder head, reported pressure rise after complete inflammation of the charge with very low compression ratios. Wawrziniok (reference 42) found maximum pressure developing in his bomb considerably after the flame front had ionized a gap at the end of the bomb. In this case the ionization gap was located at the most distant position in a hemispherical end of the bomb so that error due to curvature of flame front was minimized; yet the lag between ionization of this gap and peak pressure was about 20 percent of the total burning time. Marvin, Caldwell, and Steele (reference 59) observed that total radiation from burning gases increased after inflammation throughout a time interval equivalent to about 20° of crankshaft rotation at 600 rpm.

Bureau of Standards investigators (reference 60), taking streak photographs of combustion in a spherical bomb, suspended fine grains of gunpowder at various points on a diameter of the bomb by means of human hairs. With central ignition, the brilliantly burning grains of gunpowder continued to move toward the center of the bomb for some time after the flame reached the wall of the bomb. This experiment seems to be particularly strong evidence of afterburning in the outer parts of the bomb.

Lewis and von Elbe have done work determining the temperature zones in burner flames (reference 1). Much uncertainty would be involved, however, in applying the results to the much different conditions existing in engine combustion.

In a discussion of combustion in a turbulent stream, Shchelkin (reference 62) has drawn a model of flame structure that might well apply under the highly turbulent conditions existing during combustion in the engine cylinder. According to this model, the turbulence in the flame front causes the flame to advance in microscopic, or near microscopic, tongues. The structure behind the flame front is cellular; the cell walls constitute burning gas and the interiors of the cells constitute unignited gas. According to this model, the unignited gas within each cell is gradually consumed as the flame front progresses beyond the cell. With this structure, in the microscopic sense the burning zones might all be very thin; in the macroscopic sense a deep afterburning zone would exist behind the flame front. In any event, the preponderance of experimental evidence available at this time appears to favor the existence of a rather deep zone of combustion behind the flame front in the engine cylinder, though the main part of the combustion may take place only within a small part of this zone. Whether the combustion zone is cellular on the microscopic scale or only on a submicroscopic or molecular scale does not seem important in the presentation of the combined theory of knock. In either case there is a possibility that the gases in the combustion zone may be peculiarly susceptible to the propagation of a detonation wave, and the available evidence on this point should be carefully considered.

The concept of autoignition followed by the development of a detonation wave was given passing attention in the previously quoted remarks of Woodbury, Lewis, and Canby in reference 18. Among the streak photographs of autoignition resulting from quick compression of the charge in a glass tube, which were presented by Dixon and coworkers in references 23 and 24, were included some records of what they believed to be detonation waves. Dixon and coworkers pointed out the fact that the development of the detonation wave was always preceded by autoignition at some point within the charge. The concept of the development of a detonation wave in autoigniting end gas has also been suggested by Boerlage and van Dyck (reference 63). They pointed out that "simultaneous combustion" at the beginning should be considered as a slow pressure rise in comparison with "true detonation" but that it ultimately may have the same character. The reverse concept, autoignition triggered by a shock wave, has been suggested by Dreyhaupt (reference 64).

The concept of autoignition followed by the development of a detonation wave is consistent with the NACA high-speed motion pictures presented in references 7, 8, 9, and 16, if the explosive knock reaction is considered to be a detonation wave. In these photographs, in most cases where end gas was visible at the time of the explosive knock reaction, this reaction has been preceded by some form of apparent autoignition. In one case the apparent autoignition developed at definite centers within the end gas and spread out in all directions from those centers to fill the end zone before the explosive knock reaction occurred. (See fig. 10, reference 9.) In another case the autoignition began at the chamber wall and propagated throughout the end zone before the explosive knock reaction occurred. (See fig. 12, reference 9.) In this case the visible explosive knock reaction was light. In other cases the autoignition developed uniformly and simultaneously throughout the end zone before the explosive knock reaction occurred. (See fig. 5, reference 16.) In yet other cases, autoignition was not clearly visible in the photographs but a visible vibration of the gases of the detonation-wave type was set up before the explosive knock reaction occurred (reference 9). The occurrence of a visible vibration before the explosive knock reaction is an effect apparently not frequently encountered. It appears likely that this phenomenon is comparable with the explosive knock reaction in speed and it may, therefore, be a mild detonation wave followed later by the development of a many times more powerful detonation wave.

The evidence of references 7, 8, 9, and 16 is open to the criticism that the end-zone reactions shown before knock may not represent true flame because the schlieren system may reveal reactions much less intense than flame combustion. The same phenomenon has been shown, however, in photographs exposed by direct-flame radiation presented by Rothrock and Spencer (reference 38). With 18- and 30-octane fuels at a compression ratio of 7, photographs taken at about 2000 frames per second (fig. 7 of reference 38) showed autoignition in the end gas one frame before the development of the brilliant illumination caused by knock. In the same paper Rothrock and Spencer showed that this brilliant illumination coincided chronologically with the beginning of the gas vibrations.

The concept of a detonation wave set up in afterburning gases behind the normal flame front has been proposed previously by Maxwell and Wheeler (references 2, 3, and 44). In streak photographs of combustion in a bomb with knocking fuels they found only very faint afterglows behind the flame front during the travel of the flame through the bomb. After the flame had traveled completely through the charge they observed an extremely high-speed travel of a more brilliant glow through the chamber. With nonknocking fuels, however, the afterglow behind the normal flame front was brilliant. They reported invariably a correlation between the "pinking" tendencies of fuels and the lack of brilliancy in the afterburning and they reported that addition of ethyl ether or amyl nitrate to a fuel decreased the brilliance of the afterglow and that decomposed tetraethyl lead increased the brilliance of the afterglow. These investigators concluded in part that the tendency to knock was dependent on slow afterburning, leaving sufficient energy behind the flame front to maintain a shock wave (detonation wave) set up by collision of the flame front with the chamber wall. Lorentzen (reference 41) found evidence from experiments with a combustion bomb that he believed supported the theory proposed by Maxwell and Wheeler in references 2, 3, and 44. The finding that knocking fuels show less brilliant afterglows than nonknocking fuels has been verified by Duchêne (reference 31) and by Rothrock and Spencer (reference 38). Rothrock and Spencer have also presented in figure 12 of reference 38, 2000-frame-per-second motion pictures of combustion of 65-octane gasoline in which the combustion chamber was entirely inflamed before the occurrence of knock as indicated by very brilliant reillumination of the entire chamber. In reference 7 (fig. 4) a knocking reaction occurred not only after complete inflammation of the cylinder charge but even so late that the schlieren combustion pattern was almost gone.

The combined detonation-wave and autoignition theory, to be complete, must account for the fact that combustion cycles involving nothing more than simple autoignition have been studied by General Motors investigators (references 25, 28, and 29) and have been regarded by those investigators as knocking cycles. It is clear that gas vibrations can cause forced vibrations of the combustion-chamber walls of the same frequency as the gas vibrations and thus cause a high-pitched ping. As gas vibrations apparently did not occur in the combustion cycles of references 25, 28, and 29, however, the question naturally arises as to the cause of the knock that was heard. The only possible answer appears to be that the knocking sound was due to natural vibrations of engine parts.

The autoignition that occurred in the General Motors investigations has been seen to require a period of approximately one-thousandth part of a second for its completion. The sharp increase of pressure in the combustion chamber within the period of one-thousandth part of a second could set up natural vibrations in some of the stressed engine parts. The energy imparted to the natural vibrations by the autoignition would, in general, be greater in the case of low-frequency vibration than in the case of high-frequency vibration. The influence of vibration frequency on the energy imparted to the vibration by the autoignition could be determined mathematically only if definite information were available as to the rate at which energy is released by autoignition at each instant throughout the autoignition process. Though no such information is available, the experimental evidence at least indicates that energy is released by the autoignition in such a manner that it does not excite appreciable vibration of the gases. It may therefore be reasonably assumed that the autoignition would excite natural vibrations of the stressed engine parts only in such modes as have a natural frequency considerably less than the natural frequency of the vibrating gases.

The suggestion that "knock" is due to vibration of engine parts caused by autoignition and that "pink" is caused by gas vibrations has previously been made by Boerlage and coworkers (references 6, 37, and 63).

Summary of discussion of published work.—The following facts appear to be supported by the weight of experimental evidence:

1. Autoignition of comparatively large bodies of end gas occurs too slowly under certain conditions to produce audible gas vibrations.
2. Under suitable conditions one or both of two types of gas vibration may occur, the detonation-wave type and the vibratory-combustion type.
3. Either type of gas vibration may occur independently of autoignition, but under some conditions the detonation-wave type of gas vibration tends to occur very soon after slow autoignition has taken place.
4. Under suitable conditions apparent detonation waves can develop in the engine cylinder.
5. Under a wide range of conditions, either combustion continues for a distance sometimes as great as several inches behind the flame front or some adjustment of equilibrium takes place through the same distance resulting in increased pressure, continued ionization, and continued emission of light.

The foregoing facts, supported by the experimental evidence, suggest the following explanation of knock in the spark-ignition engine:

(a) Knock of a comparatively low pitch is caused by simple autoignition of end gas at a rate too slow to produce audible gas vibrations.

(b) Knock involving both low- and high-pitched tones may be caused by autoignition followed by the development of a detonation wave in the autoignited gases.

(c) Knock of high pitch may be caused by a detonation wave in afterburning gases behind the flame front. This detonation wave, having originated in the afterburning gases behind the flame front, may also pass through unignited end gas.

This explanation of knock harmonizes with the analysis of NACA high-speed photographs that will be developed in the second part of this section.

ANALYSIS OF NACA HIGH-SPEED PHOTOGRAPHS

Apparatus and operating conditions.—The high-speed motion pictures presented and discussed herein are not the result of a specific investigation but have been selected from the data obtained with the NACA high-speed motion-picture camera and the NACA combustion apparatus in the investigations of references 7, 9, and 16. A diagrammatic sketch of the combustion apparatus is shown in figure 1. This apparatus is a single-cylinder engine of 5-inch bore and 7-inch stroke, with glass windows in the cylinder head and a glass mirror on the piston top as shown in the figure. The visible part of the combustion chamber is 4½ inches wide, as shown at frame H–20 in figure 2. The combustion apparatus has been described in references 16 and 38. The NACA high-speed motion-picture camera is described in detail in reference 15. This camera was used to obtain photographs shown in references 8, 13, 65, and 66 as well as those presented in references 7, 9, and 16. The optical arrangement for schlieren photography will not be redescribed herein, except to state that the schlieren photographs are taken by externally supplied light projected into the combustion chamber through the glass windows and then reflected back out through the glass windows to the high-speed camera by the mirror on the piston top.

In all the investigations drawn upon for the data of the present paper, the combustion apparatus was driven by an electric motor and operated under its own power for only one combustion cycle in each run; the entire series of photographs was taken during the single combustion cycle. With the exception of slight variations noted in the original reports

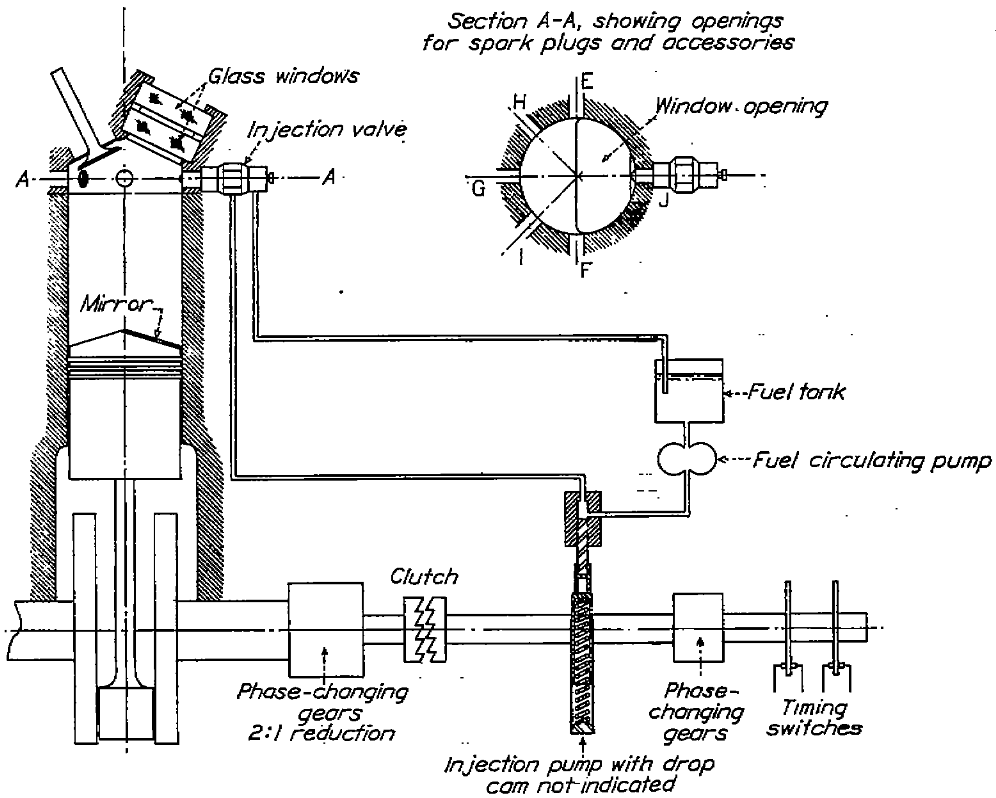


FIGURE 1.—Diagrammatic sketch of NACA combustion apparatus.

of the investigations, the following engine conditions were held constant:

Compression ratio	7.0
Jacket and head temperature, °F	250
Fuel-injection timing, degrees A. T. C. (intake stroke)	20
Spark timing, degrees B. T. C.:	
At G position (see fig. 1)	27
At E position, At J position, At F position	20
Fuel-air ratio	Approximately 0.08
Inlet-air conditions	Atmospheric
Engine speed, rpm	500

Spark timings were selected to produce knock at top center with the end gas well within the field of view. In the investigations of references 7 and 16, the injection valve was placed in opening H of the cylinder head (see fig. 1) when four spark plugs were used, but in opening J when only one spark plug was used. In the investigation of reference 9 the injection valve was always in opening H. A shrouded inlet valve was used in the investigations of references 7 and 16 to produce a clockwise air swirl, but a plain inlet valve was used in the investigation of reference 9.

Fuels used for the combustion cycles shown herein were M–2, leaded and unleaded, and blends of M–2 with S–1.

High-speed photograph of explosive knock reaction traveling at speed above 5500 feet per second.—In figure 2 is shown the same high-speed photographic shot of knocking combustion that was presented as figure 5 of reference 16. Individual photographs in figure 2, as well as in other figures, will be designated throughout this discussion as frame A–1, frame B–2, and so on. This designation will be understood to mean the first frame in row A, the second frame in row B, and so on. The order in which the photographs were taken is A–1, A–2, A–3, . . ., A–20, B–1, B–2, . . ., R–17, R–18; the photographs should be read from left to right through row A, then from left to right through row B, and so on.

Ignition, in the case of figure 2, was by one spark plug at position E. (See fig. 1.) The flame first becomes visible in the photographs as a small but growing darkened area in frames C–9 to C–20. At frame H–1 the flame front has progressed about halfway across the visible portion of the chamber and the entire region through which the flame front has passed has a dark mottled appearance. This area behind the flame front is dark and mottled instead of brilliant white because the photographs were taken by the schlieren method rather than by direct photography of the flame radiations. The schlieren method shows the effect of the flame on light that is projected through it, but the light radiated by the flame itself was too faint to be photographed in frame H–1.

At frame J–1 the dark mottling has disappeared from most of the region through which the flame front has passed. The mottling probably indicates the region in which combustion is proceeding, as was indicated in references 8 and 57. Combustion, therefore, was probably either completed or arrested in most of the space through which the flame front had traveled at the time of exposure of frame J–1.

In the frames of row K in the figure, a darkening of the region through which the flame front has not yet passed begins to be apparent. This darkening of the end gas becomes more intense throughout row L and the first frames of row M. In frame M–10 the darkening of the end gas has progressed to such a degree that the flame front can no longer be discerned. The end gas appears to be fully ignited

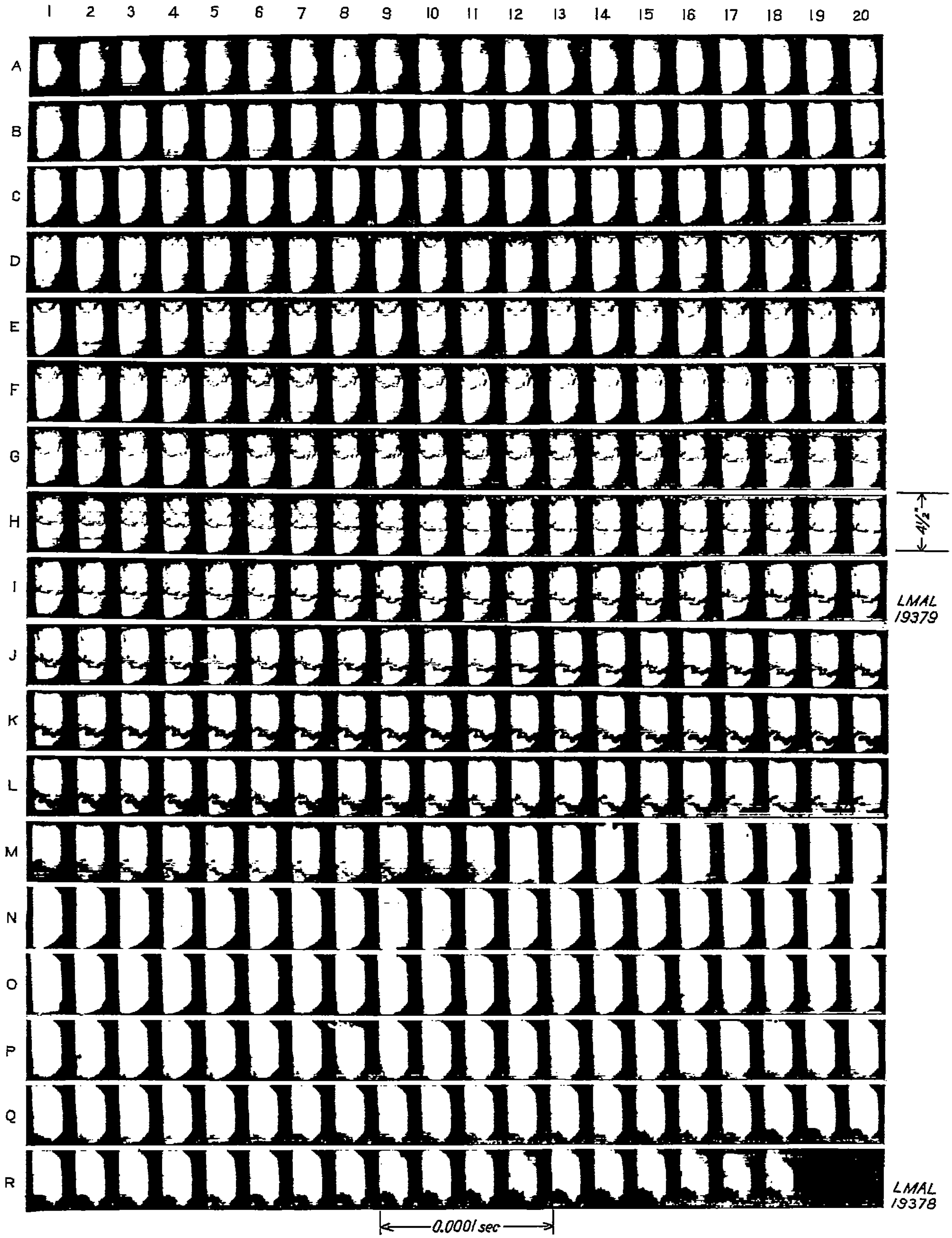


FIGURE 2.—High-speed motion pictures of knocking combustion cycle in engine cylinder showing detonation preceded by diffuse autoignition. Fuel, 50 percent S-1 and 50 percent M-2; one spark plug. (Fig. 5 of reference 16.) (See fig. 3 for enlargement of knocking portion.)

and to be burning at a rate comparable with that of the gases which have just been passed through by the flame front. Knock of the simple autoignition type has probably taken place between frames K–1 and M–10. Knock of the sort that sets up the detonation-wave type of vibration has not yet even begun in frame M–10, however, as may be clearly observed by eye when the photographs are projected on the screen as motion pictures and as has been shown by the analysis of reference 8.

The first trace of the explosive knock reaction, which causes the detonation-wave type of gas vibration, is visible in frame M–11 as a whitened region along the lower right edge of the frame. In frame M–12 the whitened region has extended over the entire frame. The whitening of frames M–11 and M–12 is caused by two factors; first, the combustion zone stops interfering with the externally supplied light by which the schlieren photographs are taken, allowing this light to come through to the camera uninterrupted; second, the knock causes a manyfold increase in the radiation from the combustion products and this radiation itself produces a whitening of the photograph.

The development of the knock in frames M–11 and M–12 suggests that the knock began at the lower right edge of the field of view and spread very rapidly toward the left. This indication was not commented on in reference 16 because it was appreciated that the focal-plane-shutter effect would draw the apparent origin of the disturbance toward the right of the frame and a satisfactory interpretation of frames M–11 and M–12 taking into account the focal-plane-shutter action of the high-speed camera had not yet been developed. The suggestion of frames M–11 and M–12, however, that the origin of the knock was at the right edge of the frame was so strong that the reverse conclusion has only recently been reached. Correctly interpreted, frames M–11 and M–12 indicate that the knocking disturbance originated near the left side of the frame or outside of the field of view to the left of the frame and moved toward the right at a speed probably considerably greater than 5500 feet per second, a speed equal to nearly twice the speed of sound in the chamber (about 3000 ft/sec) and fully as great a speed as should be expected for a true detonation wave. This interpretation will be explained in later sections.

Imaginary focal-plane shutter equivalent to shutter of NACA high-speed camera.—From a study of reference 15, it will be understood that the NACA high-speed motion-picture camera utilizes one independent focal-plane shutter for each single photograph taken by the camera. Each of the 372 focal-plane shutters consists of a single glass prism mounted alongside the motion-picture film inside a rotating drum. The focal plane through which the glass prisms, or shutters, move is not the plane of the photosensitive film but the plane in which a primary image is formed by a stationary objective lens. After the light has passed through one of the focal-plane shutters, or prisms, it proceeds through a second and a third stationary lens, which refocus the light to form a secondary image on the film. The glass prisms, in addition to their function as focal-plane shutters, also cause the secondary images formed on the film to move in the same direction and at the same speed as the film so that there is no appreciable relative motion between the images and the film and consequently no appreciable blurring of the exposure on the film.

The second and third stationary lenses of the camera not only produce a secondary image of the combustion chamber, but they also form images of the moving prisms, or focal-plane shutters. The images of the prisms, however, do not move as fast as the film but half as fast and in the same direction. Their absolute speed being half that of the film and in the same direction, their speed relative to the film is half the absolute speed of the film but in the opposite direction, that is, in a direction away from the previously taken photographs toward the photographs that are yet to be taken. Study of reference 15 will reveal that the width of the focal-plane-shutter slit, or of the prism image, on the film is half of the frame spacing, that is, half the distance from any given point in one frame to the same point in the next succeeding frame. Half of the frame spacing is approximately 70 percent of the combustion-chamber image width as it appears in figure 2 and other figures of this paper.

Hereinafter the expression "focal-plane-shutter slit" will be used as meaning not a glass prism itself but the image of a prism on the film, "focal-plane-shutter slit width" will be used as the width of the images of the glass prisms on the film, and "focal-plane-shutter speed" will be understood as the speed of the prism images relative to the film rather than the speed of the prisms themselves.

In the exposure of frames on the film, if a given point in a combustion-chamber image is located within the image of the corresponding glass prism at any instant, then that given point in the combustion-chamber image is in the process of exposure at that instant; but as soon as the motion of the prism image relative to the film causes the given point in the combustion-chamber image to pass outside the glass-prism image then the exposure is discontinued on that given point in the combustion-chamber image. The image of a glass prism on the film is therefore truly a focal-plane-shutter slit.

As may be seen from a study of reference 15, at any instant the trailing edge of any one focal-plane-shutter slit occupies the same position relative to its frame on the film that the leading edge of another focal-plane-shutter slit occupies on the next succeeding frame of the film. Consequently, as soon as any point within the combustion chamber ceases to be exposed on one frame of the film, that point begins to be exposed on the next succeeding frame of the film. All points within the combustion chamber are therefore undergoing exposure on one frame or another at all times.

The shutter arrangement shown in figure 3 bears no physical resemblance to the shutters of the high-speed camera but provides the same manner of exposure and can be much more satisfactorily represented schematically. Frames M–10, M–11, M–12, and M–13 from figure 2 are shown in figure 3 with a spatial arrangement different from that of figure 2. In the arrangement of figure 3, it is assumed that the four frames are formed on a single stationary film by four stationary objective lenses arranged above the plane of the paper on different optical axes. Just above the film an opaque screen is assumed, with rectangular openings A, B, C, and D; and this screen is assumed to move rapidly in

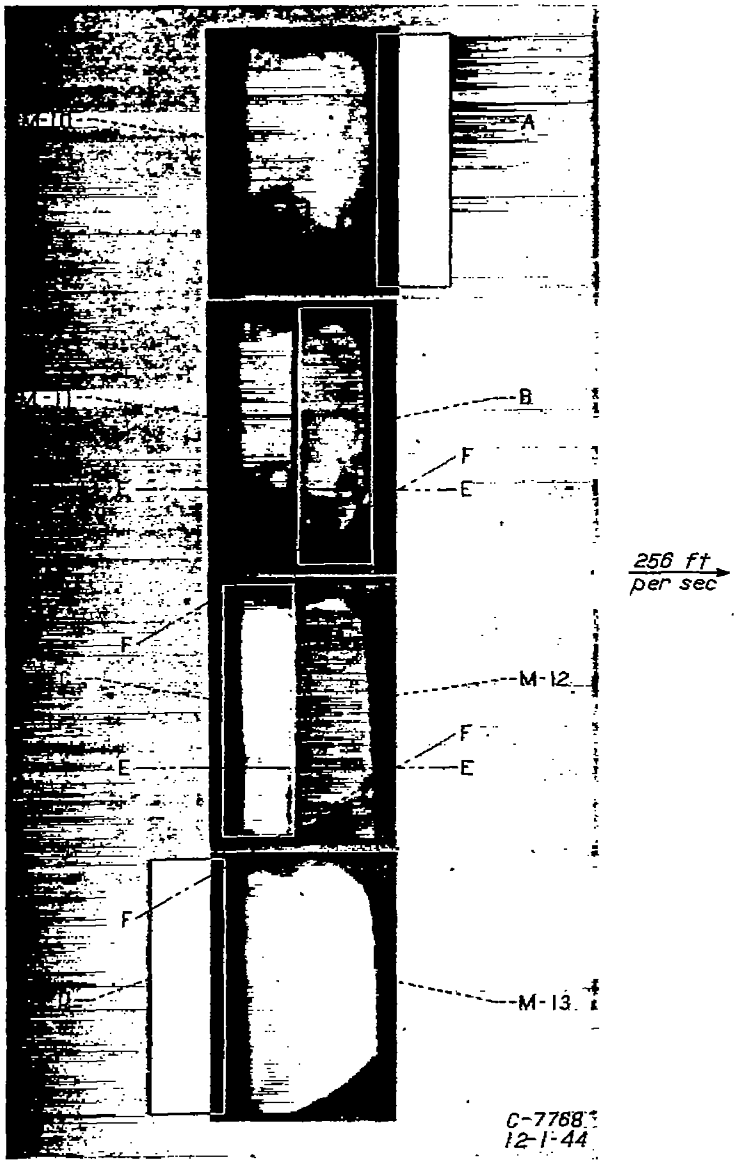
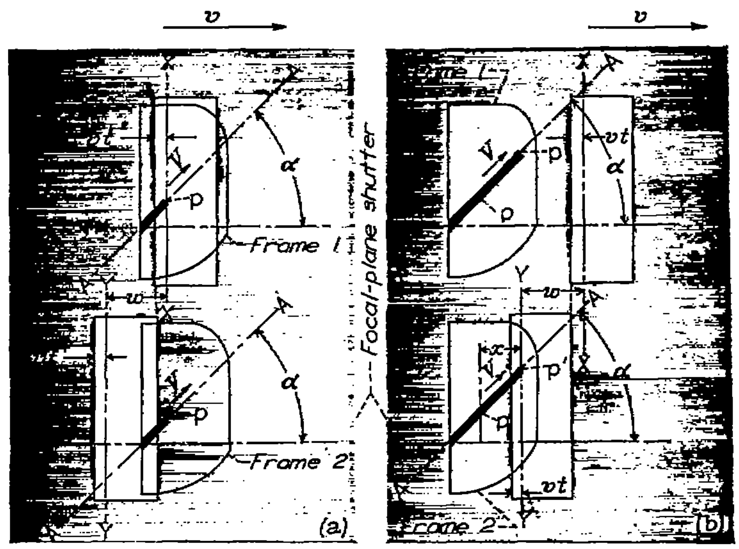


FIGURE 3.—Equivalent manner of exposure of frames in high-speed photographs. A, B, C, D, rectangular slots in an opaque screen; M-10, M-11, M-12, M-13, successive frames from knocking portion of figure 2.

the direction indicated, thus acting as a conventional focal-plane shutter. Frame M-10 is exposed by light passing through opening A as that opening passes over the frame M-10; frame M-11 is exposed by light passing through opening B; and so on. The width of the openings A, B, C, and D is approximately 70 percent of the combustion-chamber image width, as was the case in the camera. The trailing edge of opening A is in line with the leading edge of opening B, the trailing edge of opening B in line with the leading edge of opening C, and so on.

Derivation of formula for effect of focal-plane shutter on apparent speed of knock propagation.—Photographs taken with a focal-plane shutter of the type described give a false indication of velocities. The relation of the false indicated velocity to the true velocity can, however, be easily derived.

Figure 4 (a) shows schematic diagrams of two successive motion-picture frames with the focal-plane-shutter screen in one position at time T_0 and figure 4 (b) shows diagrams of the same two motion-picture frames at a later instant T with the focal-plane-shutter screen in a different position. The focal-plane-shutter screen is considered to be moving from left to right with the velocity v. A luminous ray represented by the wide black line is assumed to be developing in each of the frames of figure 4 along the line AA, making an angle α with the direction of focal-plane-shutter movement. The wide black lines shown in the frames of figures 4 (a) and 4 (b) should be understood to represent the light falling on the focal-plane-shutter screen or the photosensitive film at the instants T_0 and T, respectively; these lines do not in every case represent the final record appearing on the film. At the instant T_0, when the focal-plane-shutter screen has reached the position shown in figure 4 (a), the leading end of the luminous ray is assumed to have reached the point p in each of the frames of figure 4 (a). Obviously the point p is in the process of exposure at the instant T_0 on frame 1 of figure 4 (a) but not on frame 2 of figure 4 (a) because of interference by the focal-plane shutter. At the later instant T when the focal-plane-shutter screen has reached the position shown in figure 4 (b), the leading end of the luminous ray is assumed to have reached the point p′ in each of the frames of figure 4 (b). At the instant T the point p′ is in the process of exposure on frame 2 of figure 4 (b), but not on frame 1 of figure 4 (b) because of interference by the focal-plane shutter.



(a) Focal-plane-shutter position at time T_0. (b) Focal-plane-shutter position at time T.

FIGURE 4.—Schematic diagrams of focal-plane-shutter action.

A certain time t is assumed to be required for the leading end of the luminous ray to make a visible exposure on the film. It is assumed that luminosity in any gas particle does not develop to full intensity instantly but develops according to some unknown law after the causative disturbance has passed through that gas particle. The assumed time t is a function of the unknown law governing the luminosity development in a gas particle and also a function of the film sensitivity. The assumption is made that the time t is the same for all gas particles. In figures 4 (a) and 4 (b), a line XX has been drawn a distance vt to the right of the trailing edge of the focal-plane-shutter slit for the upper frame and a similarly located line YY has been drawn for the lower frame.

The line XX, being located in the manner indicated, is the effective trailing edge of the focal-plane-shutter slit for frame 1 and the point p will therefore be the upper-right extremity of the luminous ray as photographed in frame 1. The exposure of the ray is cut off in frame 1 at the instant T_o when the effective trailing edge of the focal-plane-shutter slit overtakes and passes the leading end of the luminous ray at the point p. Similarly, the line YY is the effective trailing edge of the focal-plane-shutter slit for frame 2 and the point p′ will therefore be the upper-right extremity of the luminous ray as photographed in frame 2, the exposure of the ray being cut off at the instant T when the effective trailing edge of the focal-plane-shutter slit overtakes and passes the leading end of the luminous ray at the point p′. Designating

V actual velocity of ray development

V' apparent velocity of ray development (progress of ray development between two successive frames as recorded photographically, divided by nominal time between exposures of the successive frames)

x component of photographically recorded progress of ray development between two successive frames in direction of focal-plane-shutter movement (See frame 2 in fig. 4 (b).)

w focal-plane-shutter slit width

$\Delta T'=\frac{w}{v}$ nominal time between exposures of successive frames (reciprocal of number of frames/sec)

$\Delta T=T-T_o$

the following equations may now be written:

$$v=\frac{w+x}{\Delta T}=\frac{w}{\Delta T'} \tag{1}$$

$$V=\frac{x}{\Delta T\cos\alpha}=\frac{xv}{(w+x)\cos\alpha} \tag{2}$$

$$V'=\frac{x}{\Delta T'\cos\alpha}=\frac{xv}{w\cos\alpha} \tag{3}$$

$$V=\frac{vV'}{v+V'\cos\alpha} \tag{4}$$

$$V'=\frac{vV}{v-V\cos\alpha} \tag{5}$$

In the special case where V and V' are in the direction of the focal-plane-shutter movement, equations (4) and (5) become:

$$V=\frac{vV'}{v+V'} \tag{6}$$

and

$$V'=\frac{vV}{v-V} \tag{7}$$

Figure 4, from which equations (1) to (7) were derived, was drawn for the special case in which the component of the luminous-ray development in the direction of the focal-plane-shutter movement is in the same sense as the focal-plane-shutter motion and at a lower rate. Similar sketches could be constructed for the cases in which the component of the luminous-ray development in the direction of the focal-plane-shutter movement is in the opposite sense to the focal-plane-shutter motion, or in the same sense but at a higher rate. Treatment of such sketches in a manner similar to the treatment of figure 4 produces the same equations (1) to (7). In development of the equations for the case in which the component of the ray development in the direction of the focal-plane-shutter movement is in the same sense as the focal-plane-shutter motion, but at a higher rate, it must be appreciated that the points p and p′ will be leftward extremities of the ray as exposed in frames 1 and 2, respectively, instead of rightward extremities as in the case of figure 4. Because the leading end of the developing ray overtakes and passes the effective trailing edges of the focal-plane-shutter slits XX and YY, the exposure is turned on at the points p and p′ instead of being cut off at those points as in figure 4. Also, the line YY being overtaken by the leading end of the developing ray before the line XX, the point p′ will be farther to the left than point p, instead of the reverse as in figure 4. The apparent velocity of ray development will therefore be in the reverse sense to the actual.

In the general application of equations (1) to (7), V should be treated as negative if its component in the direction of the focal-plane-shutter movement is in the opposite sense to the motion of the focal-plane shutter. Likewise V' should be treated as negative if its component is in the opposite sense to the focal-plane-shutter motion. In all cases α (see fig. 4) should be treated as positive and should be the smaller angle included between the direction of the ray development and the direction of the focal-plane-shutter movement.

Experimental demonstration of focal-plane-shutter effect.—High-speed motion pictures of artificially produced luminosity fronts are shown in figure 5. The luminosity fronts for these photographs were produced with an ordinary electric fan. An aperture was cut in a sheet-metal screen of approximately the same shape as the visible portion of the combustion chamber seen in the frames of figure 2 but of dimensions much smaller than those of the actual combustion chamber. The aperture in the sheet-metal screen was covered with translucent tissue paper. The high-speed camera was focused on the translucent paper target; a projection lantern was placed beyond the target and was focused to project light onto the target and through the translucent paper to the camera. The electric fan was placed as close to the target as possible, between the target and the camera, in such manner that the rotation of the blades would repeatedly interrupt the course of the light from the target to the camera. In each of the seven shots of figure 5, the motion picture shows the uncovering of the translucent paper target by the trailing edge of one of the fan blades.

The shots of figure 5 are arranged in the order of increasing fan speed up to the maximum speed used, with the fan-blade image on the film moving in the same direction as the focal-plane-shutter slit (records A to D), then in the order of decreasing fan speed from the maximum speed used with fan-blade image and focal-plane shutter moving in opposite directions (records E to G). Actual linear speed of trailing edge of fan blade and apparent linear speed as measured from the photographs are expressed in terms of v, which is the focal-plane-shutter slit speed relative to the film.

The comparison in figure 5 of the measured apparent speeds with the actual speeds reveals that the two speeds are nearly the same only when the actual speeds are low in comparison with the focal-plane-shutter speed. (See records A and G.)

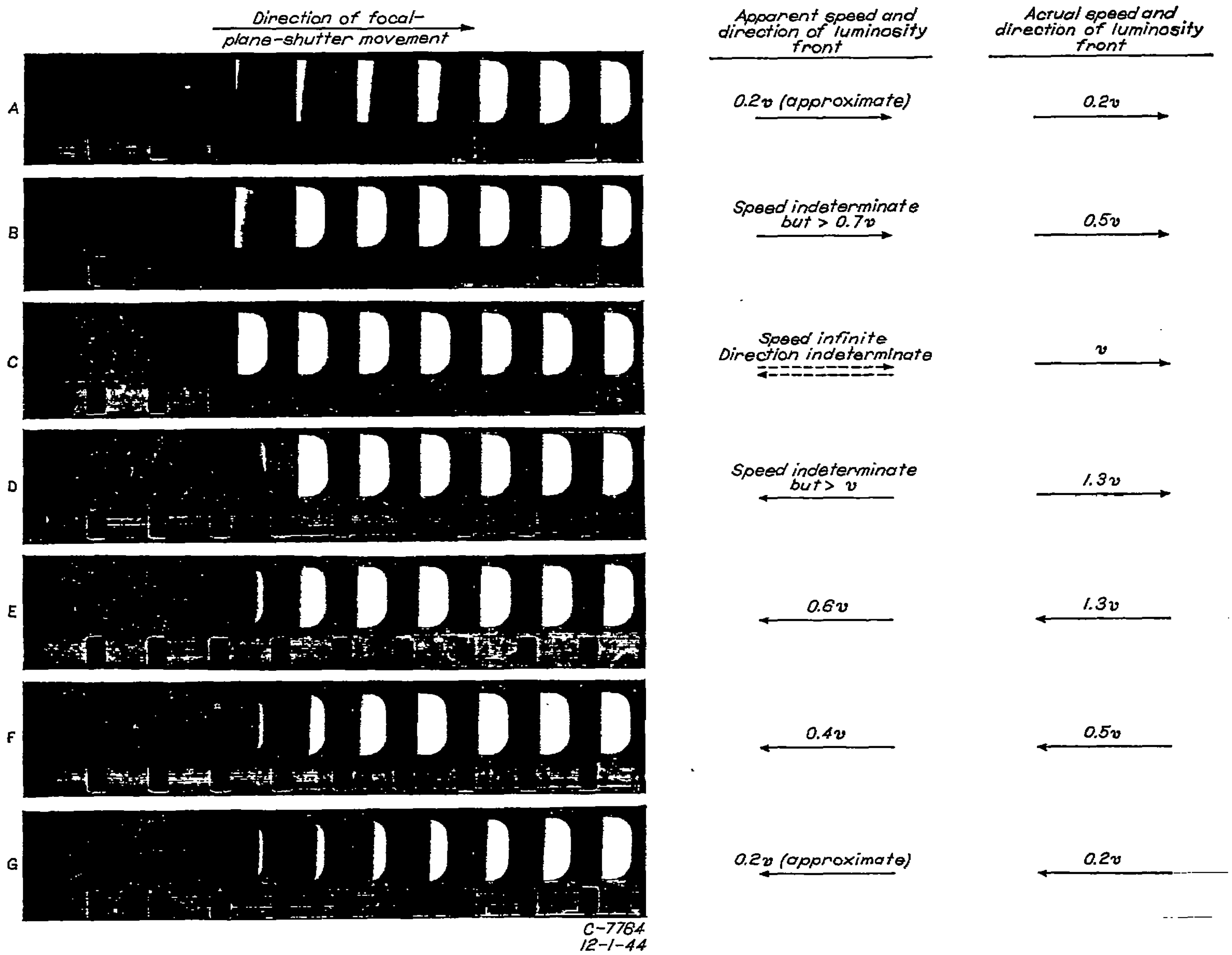


FIGURE 5.—Apparent velocity of artificially produced luminosity front.

For higher values of actual speeds the apparent speed is generally biased in the direction of the focal-plane-shutter movement. (See records B, C, E, and F.) The bias is in the direction opposite to the focal-plane-shutter movement, however, in the case of record D. As the actual speed increases from zero to infinity in the direction of the focal-plane-shutter movement and then reverses and decreases from infinity to zero in the opposite direction to the focal-plane-shutter movement, the apparent speed follows the same course but always is at a more advanced stage in the course. The reversal of direction at infinite apparent speed occurs when the actual speed is equal to and in the same direction as the focal-plane-shutter speed.

The relation between apparent and actual speeds shown by figure 5 is in agreement with equations (6) and (7).

Knock propagation rate, case 1.—In figure 3, between the exposures of frames M–11 and M–12, the apparent luminosity as measured along the line EE progressed at least all the way across the combustion-chamber image from right to left. The apparent luminosity would have progressed much farther to the left than shown in frame M–12 if the field of view had extended farther to the left. The value of x in this case is therefore between $-1.4\,w$ and $-\infty$. Application of equation (2) yields a value of $3.5\,v$ for the actual velocity of the luminosity propagation for the case of $x=-1.4\,w$, and a value equal to v for the case of $x=-\infty$; both actual velocities are in the same sense as the focal-plane-shutter movement.

If the luminosity propagation between frames M–11 and M–12 of figure 3 is measured along the line FF, a value between $-w$ and $-\infty$ is obtained for x and a value of 32° is obtained for α. Application of equation (2) to these values yields a result between ∞ and $1.2\,v$ for the actual velocity of luminosity propagation and both velocities are again in the same sense as the focal-plane-shutter movement or in the opposite sense to the apparent velocity.

When the photographic series of figure 2 was taken, the camera drum was rotating at 6620 rpm. The distance of the photographic emulsion from the center of rotation of the drum was 8.87 inches, and the linear speed of the emulsion was 512 feet per second. The focal-plane-shutter slit speed v relative to the photographic emulsion was therefore 256 feet per second. The ratio of actual combustion-chamber dimensions to dimensions of the image of the combustion chamber on the photographic emulsion was 21.5:1. In order that the luminosity front should have a speed of v=256 feet per second in the image on the film, the actual speed of the luminosity front in the combustion chamber must have been approximately 5500 feet per second. The velocity of the luminosity front as measured along the line EE in frames M–11 and M–12 of figure 3 was therefore at least 5500 feet per second, and the velocity measured along the line FF was at least 6500 feet per second.

A velocity of knock propagation in excess of 5500 feet per second can be deduced from figure 3 on a largely qualitative basis without reference to equations (1) to (7). Study of figure 3 reveals that frames M–10 and M–11 could be entirely unaffected by the knock reaction, with frames M–12 and M–13 turned completely white by the knock reaction, only if the knock reaction caused a luminosity front to move across the field of view somewhat behind the leading edge of opening C (trailing edge of opening B) and at about the same speed as the shutter motion. Further consideration of the figure makes clear that the whitened region along the lower right edge of frame M–11 could have been caused by the luminosity front overtaking the leading edge of opening C (trailing edge of opening B) shortly before the end of exposure of frame M–11. This explanation of the whitening in frame M–11 requires a speed of luminosity front somewhat greater than the speed of the shutter.

If the knocking disturbance had started at the right edge of frame M–11 and traveled to the left with infinite speed, the whitening of frame M–12 could not have extended farther to the left than the whitening of frame M–11 by a distance greater than the focal-plane-shutter slit width. With anything less than an infinite speed toward the left, the whitening of frame M–12 would have extended farther to the left than that of frame M–11 by a distance less than the focal-plane-shutter slit width. The whitening of frame M–12, however, actually does extend to the left of the whitening in frame M–11 by a distance considerably greater than the focal-plane-shutter slit width. Hence, a right-to-left movement of the disturbance is precluded.

The intense luminosity caused by the knocking disturbance probably developed not entirely in the front of the disturbance but gradually throughout a considerable distance behind the disturbance. Thus the knocking disturbance had some blurring effect throughout most of the area of frame M–11. The whitening of the edge of frame M–11 may have been caused by the development of a higher pressure at the chamber wall than elsewhere upon reflection of the knocking disturbance. The fairly uniform dark appearance of the rest of frame M–11, however, and the quite uniform whiteness of frame M–12, indicate that the speed of the knocking disturbance was at least as great as the shutter speed and in the same direction. The fact that the blurring of frame M–11 becomes progressively worse from the left edge toward the right strongly supports the belief that the knocking disturbance traveled somewhat faster than the focal-plane-shutter slit.

If travel of the knocking disturbance in the direction of the line EE in figure 3 is assumed, then it must be considered that the whitening of the lower right edge of frame M–11 was caused by the high pressure produced by reflection of the shock from the chamber walls. Otherwise, the luminosity front presumably being perpendicular to the direction of travel, the boundary of the luminosity in frame M–11 should have run in a vertical direction rather than along the cylinder wall. If travel of the disturbance approximately along the line FF is assumed, the luminosity front again being perpendicular to the line of travel, the assumption is no longer necessary that the whitening along the lower right edge of frame M–11 is caused by the high pressure of reflection. It is to be expected, rather, that when the luminosity front first began to overtake the effective trailing edge of slit B in figure 3 it did so only at the lower extremity of the chamber.

Inasmuch as hundreds of other high-speed photographs have shown no tendency toward more rapid illumination at the chamber walls than elsewhere, travel of the knocking disturbance approximately along the line FF appears to be the more reasonable explanation of the appearance of frame M–11. Because the luminosity along the line FF in this frame is continuously brighter from the lower left toward the upper right, the speed of the luminosity development must have been greater than $\frac{v}{\cos 32°}=1.18\ v$ in the image on the film and greater than 6500 feet per second in the combustion chamber. This result checks with the speed of the order of 6500 feet per second determined by Sokolik and Voinov (reference 5) and with the speed that should be expected of a true detonation wave.

Knock propagation rate, case 2.—By use of equation (2) a somewhat lower propagation speed is deduced from the photographs of figure 6 than from those of figures 2 and 3. Figure 6 is the same as figure 8 of reference 16. The combustion process in this case involved not only knock but also hot-spot ignition, or preignition. The single spark plug was in position E in the cylinder head and the hot spot in position F. (See fig. 1.) The flame from the spark plug comes into view in frames E–1 to E–17 of the figure; the flame from the hot spot, in frames A–1 to A–17.

Knock first appears in figure 6 as a slight blurring of the combustion zone in frame N–12. In the next frame N–13, a number of brightly luminous spots appear near the right edge of the frame and the area covered by such luminous spots increases in frames N–14, N–15, and N–16. Frames N–12 to N–16, covering the development of the luminous spots, are shown greatly enlarged in figure 7 for more convenient study.

Some of the luminosity in frames N–13 and N–14 of figure 7 appears outside the normal field of view. The appearance of luminosity outside the field of view at the time of knock has been explained in reference 16. This luminosity develops in gases occupying a pocket between the glass window and the metal of the cylinder head. This pocket is ⅟₁₆-inch thick and is caused by the presence of a ⅟₁₆-inch-thick gasket. The pocket is not visible in most of the frames of figures 6 and 7 because the cylinder-head surface, which forms one wall of the pocket, is not adjusted for schlieren photography as is the mirror on the piston top.

In the calculation of the speed of the knock propagation by

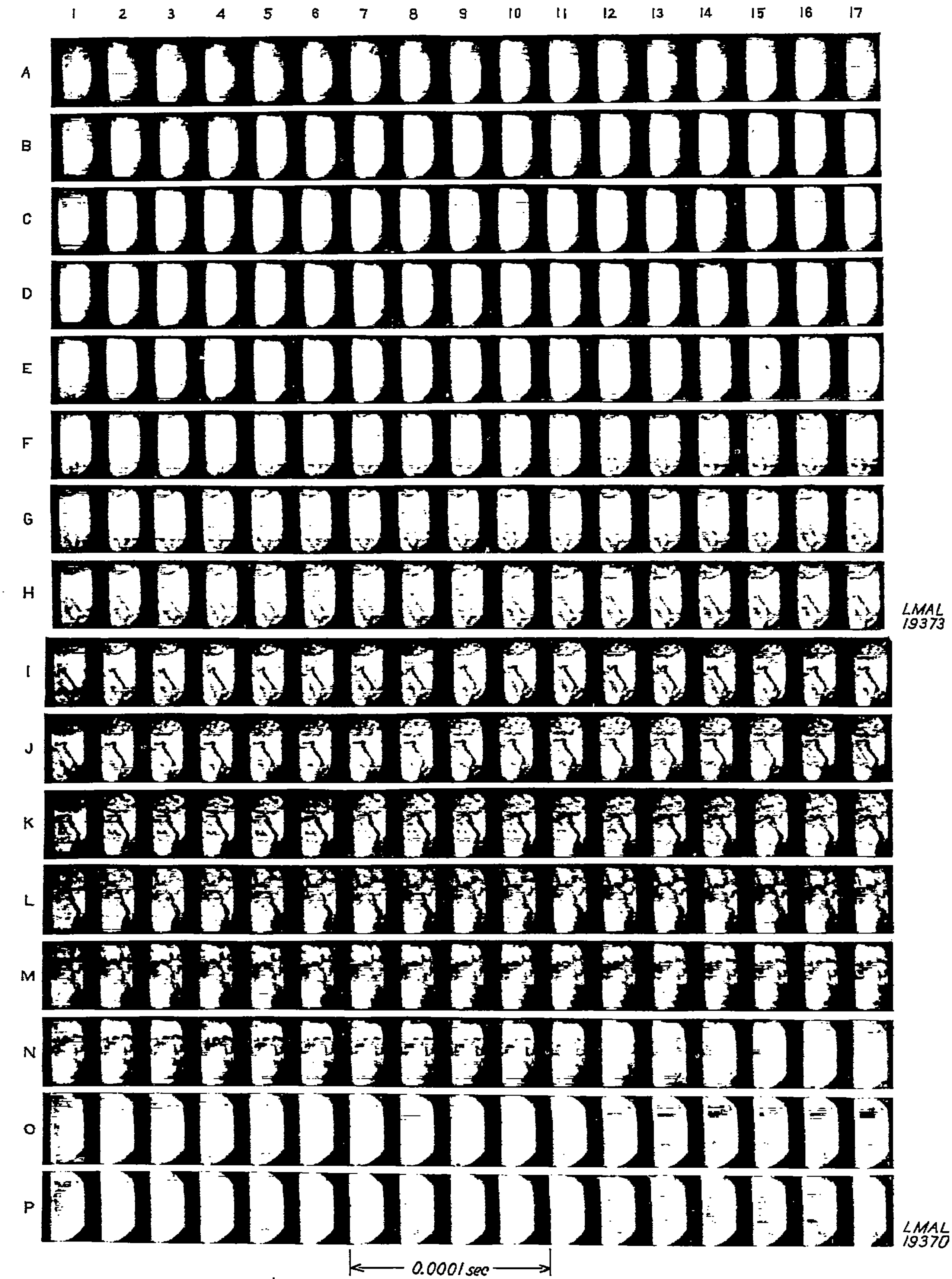


FIGURE 6.—High-speed motion pictures of knocking combustion cycle in engine cylinder showing detonation apparently not preceded by autoignition with shell-burst effect of bright luminous spots. Fuel, 50 percent S-1 and 50 percent M-2; spark plug at top, hot spot at bottom. (Fig. 8 of reference 16.) (See fig. 7 for enlargement of knocking portion.)

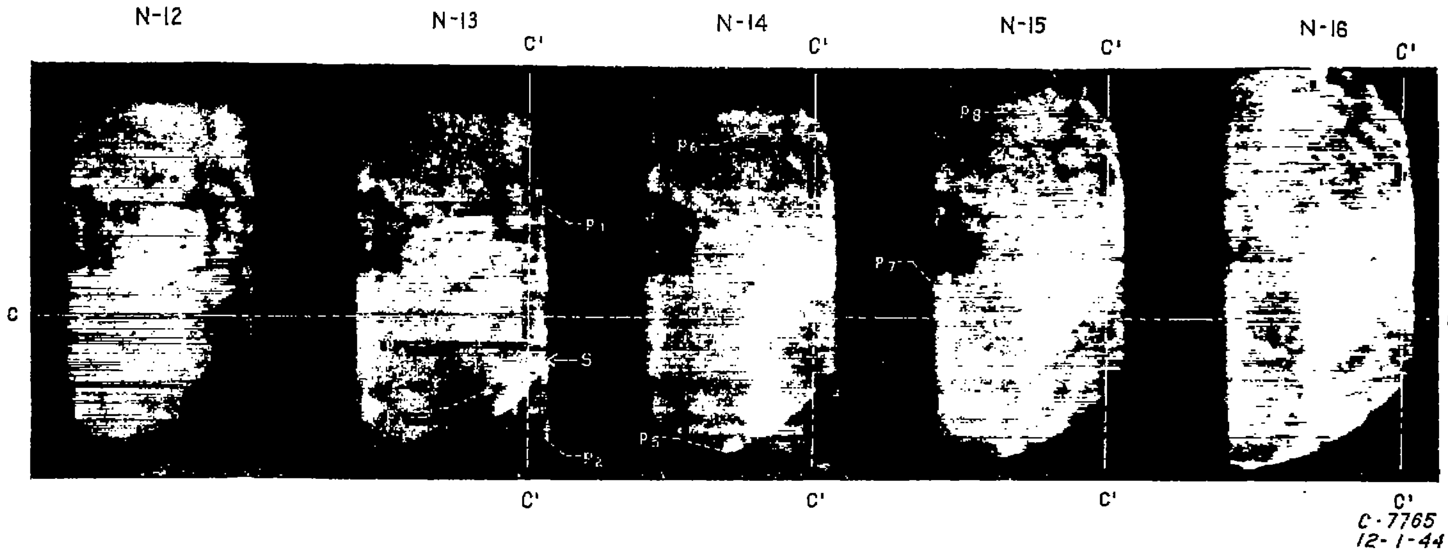


FIGURE 7.—Enlarged view of knock development as seen in frames N-12 to N-16 of figure 6

comparison of frames N–13, N–14, and N–15 with frame N–12 in figure 7, the assumption is made that frame N–12, had its exposure been completed an infinitesimal time later than was actually the case, would have shown a very small luminous spot which could have been regarded as the apparent center of the knocking disturbance. Because of this assumption, the values determined from the frame comparisons will be minimum values only; the actual propagation rate may have been higher.

Consideration of frame N–13 in figure 7 leads to the conclusion that the center of the knocking disturbance was on the line CC, because the points p_1 and p_2 marking the extremities of the luminous region are equidistant from the line CC and are in the same vertical line. (The focal-plane shutter would have equal falsifying effects on the propagation speeds from a point source to each of two limit points in the same vertical line with each other, if equal speeds are assumed, regardless of the fact that the point source may not have been on the vertical line connecting the two limit points.) The center of the knocking disturbance can be located from right to left along the line CC by consideration of points p_1, p_2, and p_3, in frame N–13, with the assumption that the knocking disturbance traveled from the center of the disturbance to point p_3 at the same speed as to the points p_1 and p_2. For the purpose of such a determination the following designations will be made:

- x_n component distance of any point p_n from center of knocking disturbance, measured to right along line CC
- h_n distance of point p_n from line CC
- α_n angle α defined in figure 4 for travel of knocking disturbance to point p_n
- V_n actual velocity of motion of knocking disturbance from center of disturbance to point p_n
- S distance of center of disturbance from right-hand edge of frame

The following tabulation shows the values of V_1, V_2, and V_3 for various assumed values of S (in all cases $h_1=h_2=0.90\ w$ and $h_3=0.44\ w$). Value of velocity or distance is expressed in each case as a dimensionless ratio:

S/w	$\frac{x_1}{w}$ or $\frac{x_2}{w}$	$\frac{x_3}{w}$	α_1 or α_2 (deg)	α_3 (deg)	$\frac{V_1}{v}$ or $\frac{V_2}{v}$	$\frac{V_3}{v}$
0.00	0.00	−0.44	90.0	45.0	0.90	−1.11
.11	.11	−.38	83.0	53.1	.82	−.82
.20	.20	−.24	77.5	61.4	.77	−.66
.30	.30	−.14	71.6	72.4	.73	−.54

The tabulation shows that in order for V_1 and V_2 to equal V_3 in numerical value the center of the knocking disturbance must have been located at a distance of 0.11 w from the right edge of the frame. The center of the disturbance in each frame of figure 7 therefore appears to have been at the intersection of lines CC and C′C′, the lines C′C′ being constructed with $S=0.11\ w$.

The speed of the knocking disturbance may now be computed for its travel to each of the most advanced bright spots in frames N–13, N–14, and N–15. In the comparison of frames N–14 and N–15 with frame N–12, equation (2) is modified by replacing w with $2w$ and $3w$, respectively. The results of such computations as compared with those of p_1, p_2, and p_3 are shown in the following table:

Point	Frame	$\frac{x_n}{w}$	$\frac{h_n}{w}$	Speed of image of knock propagation to point p_n relative to v	Speed of knock propagation in combustion chamber, (ft/sec)
p_1	N–13	0.11	0.90	0.82	4500
p_2	N–13	0.11	.90	.82	4500
p_3	N–13	−.33	.44	.82	4500
p_4	N–13	−.43	.00	.76	4200
p_5	N–14	−.71	.87	.87	4800
p_6	N–14	−.39	1.41	.91	5000
p_7	N–15	−1.10	.15	.58	3200
p_8	N–15	−.64	1.79	.80	4400

The speed of propagation of the knock of figures 6 and 7 was apparently quite appreciably lower than that of figure 2, being of the order of 4500 feet per second or one and one-half times the speed of sound in the chamber instead of about twice the speed of sound as in figure 2. Moreover, the results of the computations show that the propagation must have slowed down very quickly to the speed of sound after passing the point p_4 in frame N–13, for its speed to the point

p_7 in frame N–15 was only 3200 feet per second. The speed of propagation might be expected to drop to the speed of sound some time after the disturbance passed point p_4 in frame N–13 because p_4 was near the boundary of the mottled combustion zone as seen in frame N–12. The shock wave can maintain a speed greater than that of sound only if supported by the release of energy at the shock front. Inasmuch as the fading out of the mottled zone has been shown in references 8 and 57 to represent the completion of combustion, energy should not be expected to be available for release in the shock front after that front passes out of the mottled zone. The deceleration of the disturbance in the general direction of points p_4 and p_7 is further indicated by the fact that the mottled combustion zone visible just above the center of the frame near the left side does not disappear until about frame N–16.

Knock propagation rate, case 3.—Very few high-speed photographs have been obtained in which the center of the knocking disturbance could be located in the manner used in the analysis of figure 7. In that analysis the assumption was made that frame N–12, had it been exposed only very slightly later than it was, would have shown a very small luminous spot that could have been regarded as the apparent center of the knocking disturbance. This assumption appeared reasonable in that case because the blurring of the mottled combustion zone, which precedes the development of the luminosity, was well developed in frame N–12 of figure 7. This assumption is not reasonable, however, in the case of the knock that developed between frames G–11 and G–12 of figure 8, shown greatly enlarged in figure 9, because the blurring of the mottled zone had not even begun to develop during the exposure of any part of frame G–11. Although a luminous region appears in the lower right-hand area of frame G–12, it is likely that this luminosity began to develop an appreciable time after the beginning of exposure of the area in frame G–12.

Figure 8, which is the same as figure 7 of reference 7, shows a clear view of autoigniting end gas in frames G–1 to G–11. As it does not seem possible to determine the center of the knocking disturbance in frame G–12 by the method used in the analysis of figure 7, the center of the disturbance will be assumed for the purpose of the present analysis to have been located at the center of the autoigniting end gas visible in frames G–1 to G–11. Inasmuch as the entire

FIGURE 8.—High-speed motion pictures of knocking combustion cycle in engine cylinder showing detonation preceded by diffuse autoignition. M-2 fuel; four spark plugs. (Fig. 7 of reference 7.) (See fig. 9 for enlargement of knocking portion.)

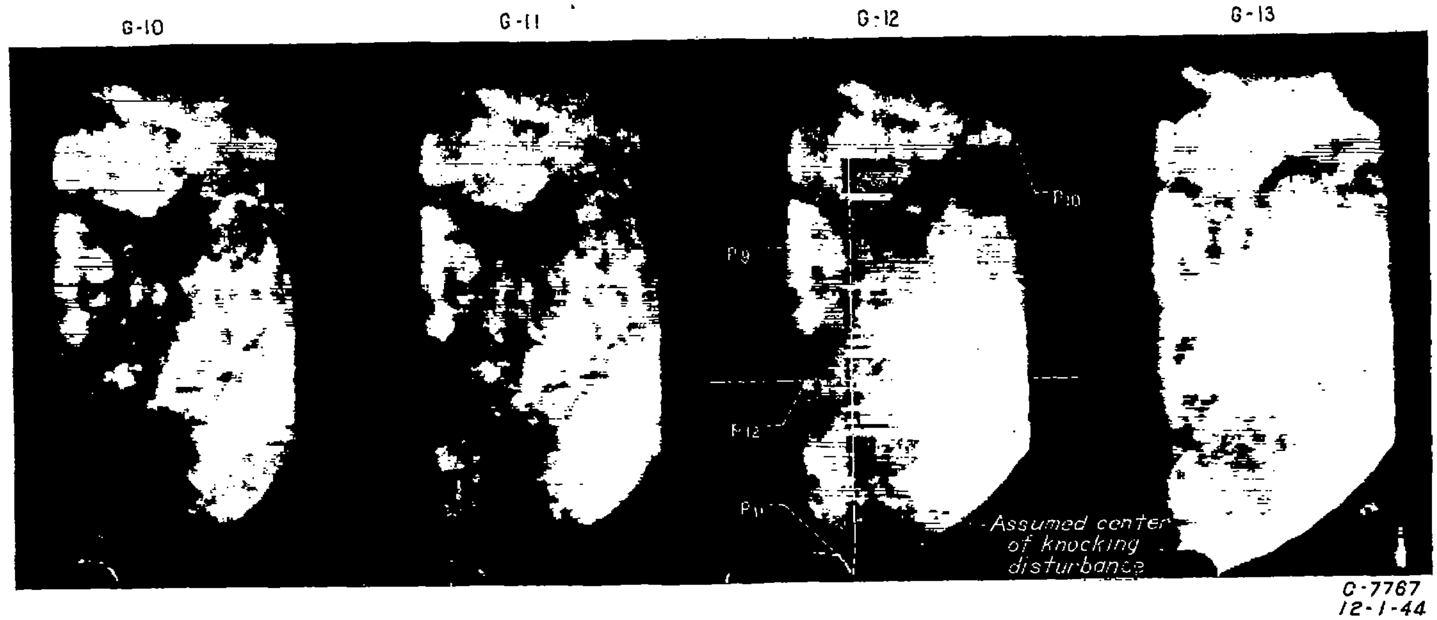


FIGURE 9.—Enlarged view of knock development as seen in frames G-10 to G-13 of figure 8.

mottled combustion zone of frame G–11 appears quite sharply defined, the blurring of the combustion zone in frame G–12 will be used as the criterion as to whether the knocking disturbance passed any particular point during the exposure of frame G–12.

Points p_9, p_{10}, and p_{11} of frame G–12 may be regarded as approximate limits of the blur of the combustion zone as these points appear only slightly blurred. Point p_{12}, on the other hand, is obviously not a limit of the spatial extent of the blurring but is simply the arbitrary limit of the field of view, inasmuch as the blurring of this point is very marked.

The speeds of the knock propagation to the three points regarded as limits of the knocking blur have been computed with equation (2) as follows:

Point	Speed of image of knock propagation to point p_n relative to v	Speed of knock propagation in combustion chamber, (ft/sec)
p_9	1.27	6900
p_{10}	.98	5400
p_{11}	.96	5200

To the three widely separated points that may be regarded as approximately marking the spatial limits of the blur in frame G–12, the propagation speed of the knocking disturbance appears to have been approximately twice the speed of sound. This determination involves the assumption that blurring began at the center of the disturbance immediately after the exposure of that center in frame G–11 and the values are therefore minimum limits. The fact that frame G–12 is progressively more blurred and more luminous from the left to the right indicates that the actual speed of the knock propagation was considerably above the values calculated for points p_{10} and p_{11}.

The knock propagation maintained a speed about twice that of sound all the way to points p_9 and p_{10}, in contrast to the case of figure 7 where the propagation slowed down to about the speed of sound in its course to the point p_7. The entire course from the knock center to the points p_9 and p_{10} lay within the mottled combustion zone and there should consequently have been unreleased chemical energy available throughout the entire course to support the propagation of the detonation wave. The travel at the higher speed to the points p_9 and p_{10} was probably for that reason.

Knock propagation rate, case 4.—Figure 10, a reproduction of figure 11 of reference 9, is the shot previously referred to in which autoignition started at various point centers scattered throughout the end gas and slowly spread out in all directions from each of those point centers until it filled the end zone. (See frames F–13 to G–10.) Frames G–10 to G–13 of figure 10 are shown greatly enlarged in figure 11. The beginning of the knocking blur is probably just discernible in frame G–10 of figure 11. In frame G–11 the blur has spread over the entire combustion zone and the points p_{13}, p_{14}, and p_{15} locate the angles of a roughly triangular bright luminous region in the same frame. Solving for equal speeds of propagation of the luminosity to the points p_{13}, p_{14}, and p_{15} locates the center of the knocking disturbance at the intersection of lines CC and C′C′ with $S=0.44\ w$ and propagation speed of about 2640 feet per second. As in the previous cases, the value of 2640 feet per second is a minimum value only and may be below the true value. That the true value actually is somewhat higher is indicated by the computation for the point p_{16} in frame G–12. With the knock center determined from frame G–11, the calculated propagation speed to the point p_{16} is 3020 feet per second. The error caused by the uncertainty as to the instant of start of the knocking disturbance is a smaller percentage of the true speed in the comparison of frame G–12 with frame G–10 than in the case of comparison of adjacent frames.

The error caused by uncertainty as to time of the beginning of the knocking disturbance affects the value of S as well as the speed of the disturbance. If the assumption is made that the disturbance began too late by a time interval t', during which the focal-plane shutter moved a distance l, to cause even a very small luminous spot on frame G–10 of figure 11, then values of S and of l may be found that will give equal

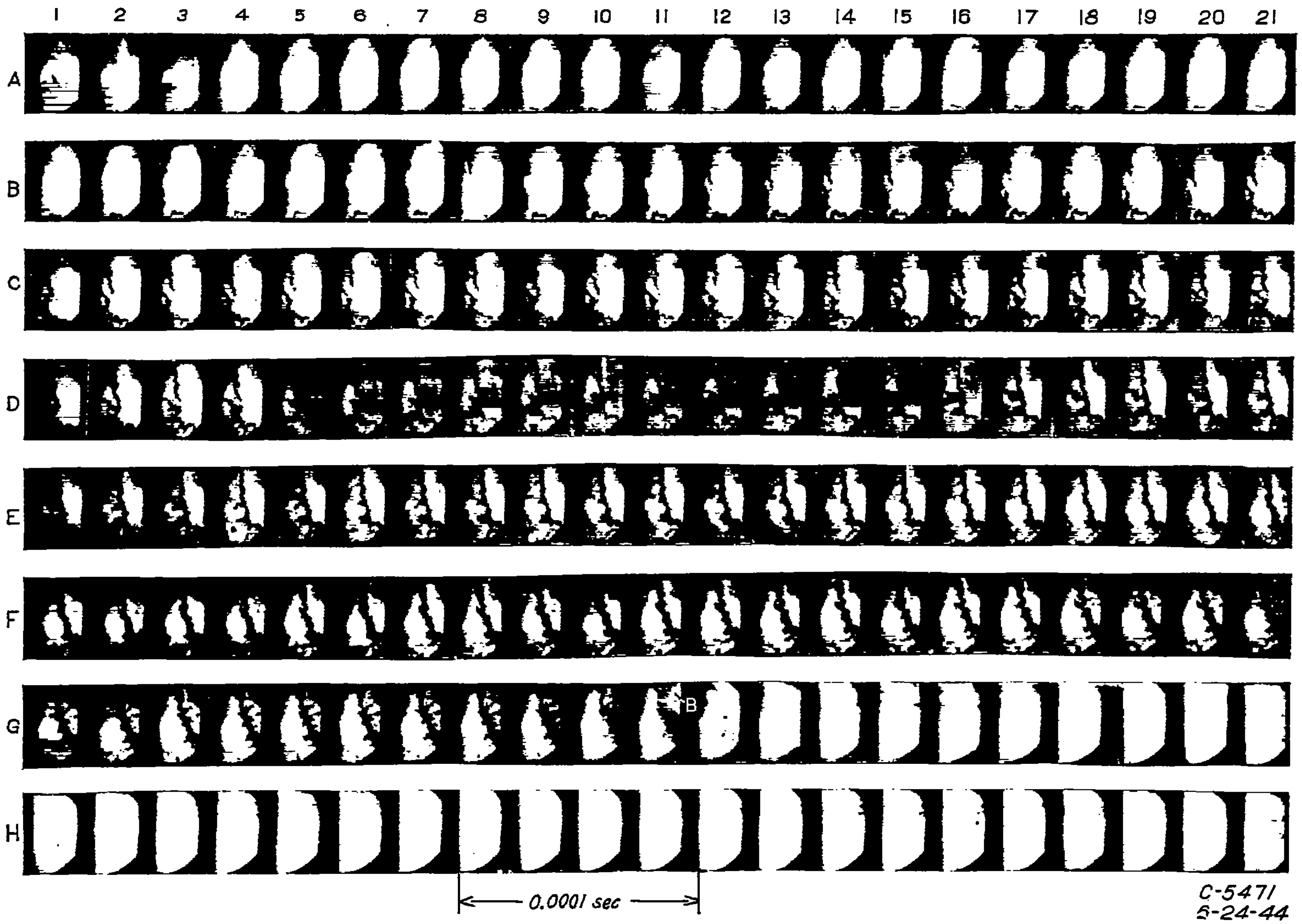


FIGURE 10.—High-speed motion pictures of knocking combustion cycle in engine cylinder showing detonation preceded by pin-point autoignition. S-1 fuel plus 200 ml amyl nitrate per gallon; two spark plugs. (Fig. 11 of reference 9.) (See fig. 11 for enlargement of knocking portion.)

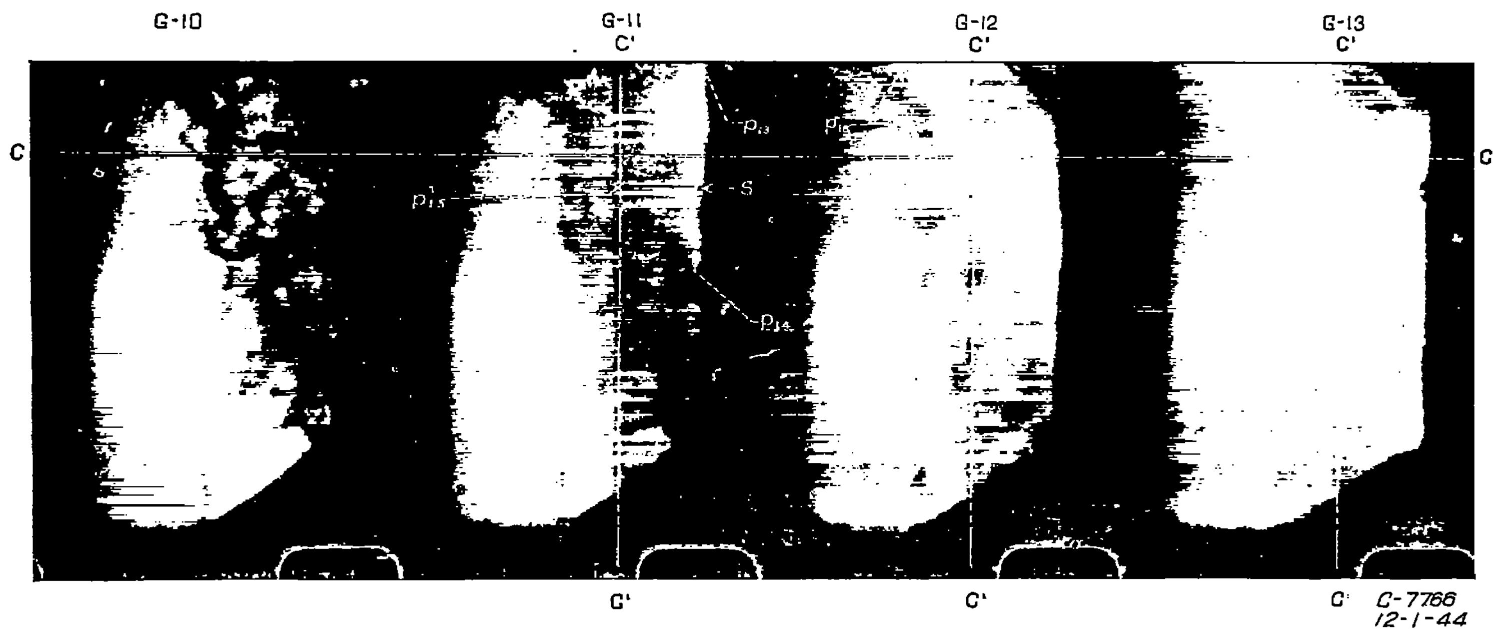


FIGURE 11.—Enlarged view of knock development as seen in frames G-10 to G-13 of figure 10.

speeds of the disturbance from its center to points p_{13}, p_{14}, p_{15}, and p_{16}. For this purpose the following equations will be used:

$$V=\frac{xv}{(w+x-l)\cos\alpha} \tag{8}$$

$$V=\frac{xv}{(2w+x-l)\cos\alpha} \tag{9}$$

equation (8) for points in frame G–11 and equation (9) for the point in frame G–12. Equal speeds to the points p_{13}, p_{14}, p_{15}, and p_{16} are obtained with $S=0.50w$ and $l=0.36w$. The speed of knocking disturbance obtained is 3630 feet per second, which is probably more accurate than either the value of 2640 feet per second or 3020 feet per second. The speed of the knock disturbance of figures 10 and 11 appears to be only of the order of the speed of sound in the chamber.

Knock propagation rate, case 5.—Another photograph showing a knock propagation rate of the lower order is seen in figure 12, a reproduction of figure 10 of reference 7. As was explained in reference 7, the camera was run in reverse for the taking of this shot and, inasmuch as the individual frames are shown in the order in which they were taken, the frames are inverted and reversed from right to left relative to their appearance in the other figures. The focal-plane-shutter motion, however, was still in the direction from left to right as seen in the figure, or in the direction from the previously taken frames toward the frames yet to be taken.

The speed of the knock propagation can be determined very much more positively and simply in the case of figure 12 than with any of the other figures. Frames C–3 to C–7 of this figure are shown enlarged in figure 13. Frame C–3 shows no evidence of knock, frame C–4 shows a well-defined luminous region of approximately circular shape that extends upward to a considerably higher level in frame C–5, and frame C–6 shows a luminous spot just beginning to develop

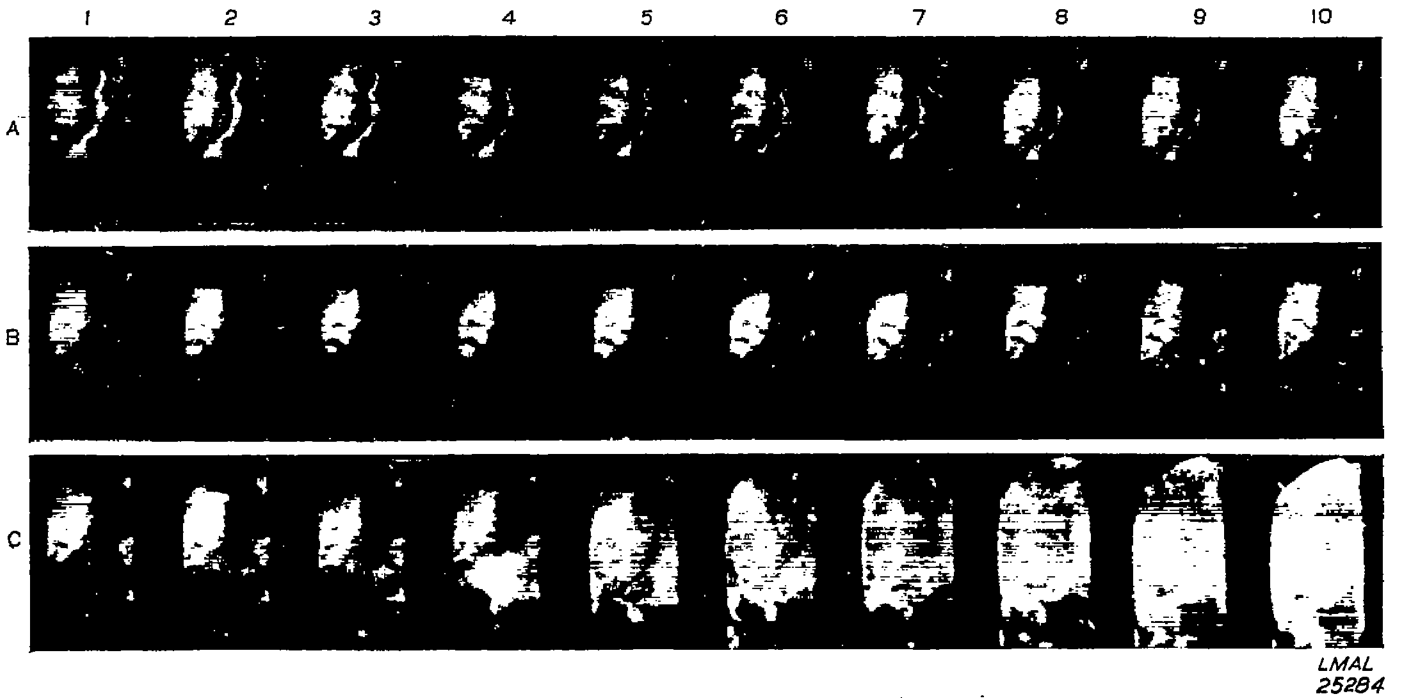


FIGURE 12.—High-speed motion pictures of part of knocking combustion cycle in engine cylinder showing detonation after flame fronts had traversed all visible parts of combustion chamber M–1 fuel; four spark plugs. (Fig. 10 of reference 7.) (See fig. 13 for enlargement of knocking portion.)

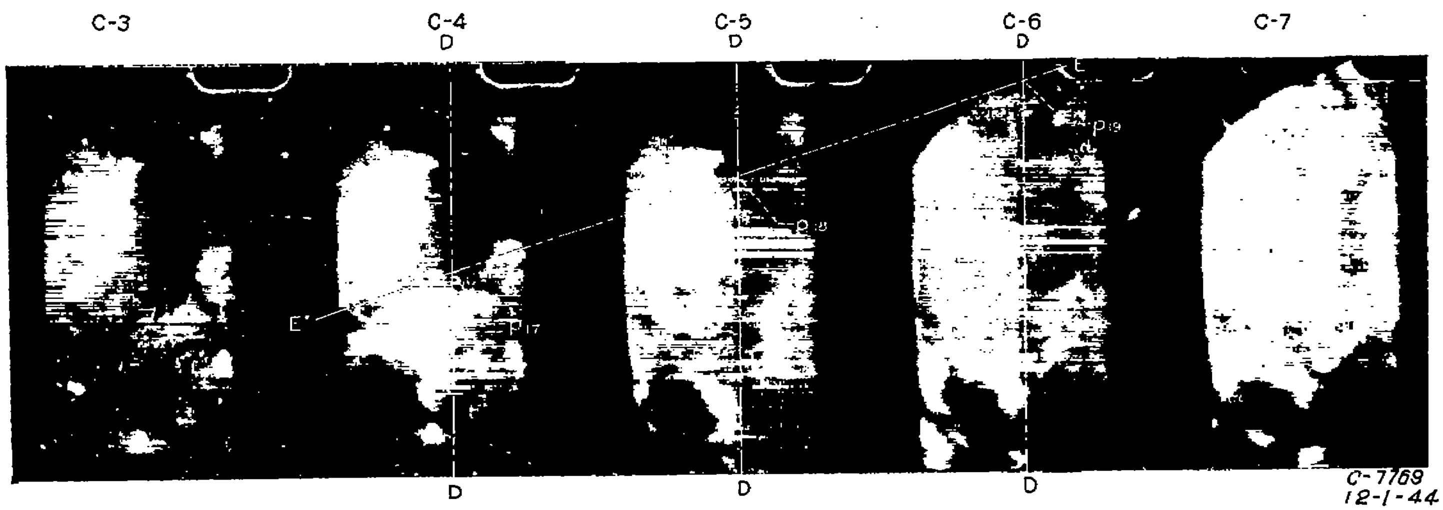


FIGURE 13.—Enlarged view of knock development as seen in frames C–3 to C–7 of figure 12.

at the point p_{19}. A vertical line DD has been drawn through the point p_{19} in frame C–6 and similar lines DD have been drawn through frames C–4 and C–5, in each case at the same distance from the right-hand edge of the frame as in frame C–6. In frames C–4 and C–5 the points p_{17} and p_{18} have been selected on the line DD and at the boundary of the blurred luminous region. As seen in the figure, a straight line EE can be drawn through the points p_{17}, p_{18}, and p_{19}; the speed of propagation was therefore the same between frames C-4 and C–5 as between frames C–5 and C–6. The points p_{17}, p_{18}, and p_{19} all being at the same distance from the right-hand edge of the frame, the actual speed of propagation along the line DD was equal to the apparent speed and is calculated to be 3400 feet per second, only of the order of the speed of sound in the chamber. (When $\alpha=90°$, equation (2) is indeterminate but equation (4) may be derived independently in the form $V=V'$ for this special case.) The true direction of travel of the knocking disturbance possibly made a slight angle with the lines DD in figure 13, in which case the true speed of propagation of the disturbance would have been somewhat less than the speed measured along the lines DD. The fact that the circle of luminosity in frame C–4 does not extend entirely to either the right or the left edge of the frame is clear evidence that the propagation rate was far below v in the image and therefore far below 5500 feet per second in the combustion chamber. Under this condition the origin of the knocking disturbance was necessarily within the blurred luminous circle of frame C–4; consequently, rectilinear travel of the disturbance from the center to the point p_{19} could not have been at an angle greater than about 18° to the lines DD and the true propagation speed could not have been less than 3400 cos 18° or about 3250 feet per second. The values of 3400 feet per second and 3250 feet per second in this case are not minimum values. The propagation speed of the knocking disturbance as indicated by the development of the blurred luminous zone was definitely between these two speeds.

CORRELATION OF RESULTS

Two of the determinations from the NACA photographs have shown propagation speeds for the knocking disturbance in excess of 5500 feet per second, one has shown a speed of the order of 4500 feet per second, and two have shown speeds somewhat over 3000 feet per second. The two determinations of 5500 feet per second are definitely minimum speeds, whereas one of the lower determinations established definite upper and lower limits of 3400 feet per second and 3250 feet per second. The discrepancy between these determinations is approximately 2:1, but the difference nevertheless appears to be real. Observation of hundreds of shots as motion pictures projected on a screen at the rate of 16 frames per second has revealed that extreme variation in knock-propagation rates actually does exist. With violent knocks such as that of figure 2 the explosive knock reaction appears quite instantaneous, entirely too fast to be followed by eye. On the other hand, knock has been obtained, in a large autoignited end zone, so light that no gas vibrations are apparent. In this case the propagation of the explosive knock reaction through the burning gases can be easily followed by eye and its speed appears to be even somewhat lower than 3000 feet per second. Unfortunately, this very slow traveling knock disturbance is so diffuse that its boundaries cannot be observed in examination of individual frames, although the spatially progressive reaction is observed unmistakably in the integrated effect of numerous successive frames provided by the motion-picture projector.

The propagation speeds in excess of 5500 feet per second are of the correct order to be regarded as detonation waves and are in agreement with the previously mentioned results of Sokolik and Voinov (reference 5). A detonation wave, however, should be expected to have lower propagation speeds as the energy released in the wave front is diminished. The propagation speeds ranging down to the speed of sound may thus be explained on the basis of detonation waves traveling through gases which have already released the greater part of their chemical energy and which therefore have little energy left to support a detonation wave. The speed of the detonation wave would be reduced as a function of the amount of energy released by autoignition or by afterburning before the detonation wave was set up.

Knock propagation at speeds below the speed of sound could not be explained on the basis of detonation waves. Though the mean speed of sound in the chamber is about 3000 feet per second after combustion is complete (reference 8), the speed of sound in the end gas just after the detonation wave has passed may be considerably below this value for three reasons: First, the temperature of the later-burned parts of the charge is well known to be lower than that in the earlier-burned parts of the charge because of adiabatic compression of the earlier-burned parts by the later-burned parts (references 67 and 68); second, because some stages of the burning may be completed a few microseconds after the front of the detonation wave has passed through the gas instead of immediately behind the wave front; and, third, because the knock reaction is known to render a part of the chemical energy unavailable, probably because of liberation of free carbon (reference 66). Instances of speed of knock propagation somewhat below 3000 feet per second would therefore be entirely compatible with the combined autoignition and detonation-wave theory. They would not be compatible with the simple autoignition theory because this theory calls for simultaneous ignition of end gas rather than a high speed of flame propagation. The variable propagation rates are not compatible with the simple detonation-wave theory, that is, with a theory independent of predetonation end-gas reaction, because such variable rates require variable concentrations of available energy explainable only by predetonation reaction in the end gas.

CONCLUSIONS

Study of the available literature concerning spark-ignition engine knock has led to the suggestion of a combined autoignition and detonation-wave theory according to which:

1. Knock of a comparatively low pitch may be caused by simple autoignition of end gas at a rate too slow to produce audible gas vibrations.

2. Knock involving both low- and high-pitched tones may be caused by autoignition followed by the development of a detonation wave in the autoignited gases.

3. Knock of high pitch may be caused by a detonation wave in afterburning gases behind the flame front. This detonation wave, having originated in the afterburning gases behind the flame front, may also pass through unignited end gas.

Application of a formula derived from an analysis of the focal-plane-shutter effect of the NACA high-speed camera to five shots of knocking combustion taken with that camera leads to the following conclusions concerning the explosive knock reaction, which is the cause of knocking gas vibrations as seen in the photographs:

(a) The explosive knock reaction is actually a self-propagating disturbance traveling through the last parts of the gas to burn.

(b) The speed of the explosive knock reaction ranges from about the speed of sound in the combustion chamber to approximately twice the speed of sound.

(c) The speed range of the explosive knock reaction is compatible with the proposed combined autoignition and detonation-wave theory but not with either of the simple theories of autoignition or detonation of the end gas.

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